MACHINE CASTING OF FERROUS ALLOYS

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ABSTRACT

This is the first semi-annual report describing research conducted at the University of Illinois at Urbana-Champaign as part of a joint university-industry research program on machine casting of ferrous alloys. It covers a period of six months starting October 1, 1975. At the time of initiation of this work the overall program had already been in effect for 33 months. During the six months covered by this report work was performed on the following subjects. (1) A variety of casting systems were designed, constructed and operated. These included transparent, low and high temperature continuous slurry producers and a laboratory casting machine. (2) Work was carried out to determine the effect of cast (Rheocast) structure on homogenization heat treatment response and mechanical properties of high temperature alloys. (3) An economic analysis of the new machine casting process was initiated.

The NH_4Cl-H_2O system was Rheocast in the transparent continuous slurry producer. The use of a rotor with a square cross section eliminated flow instabilities (Taylor Rings) generally observed in the lower mixing chamber. In the alloy systems, increasing the average cooling rate during continuous slurry production reduces the primary solid particle size. In the Sn-15%Pb and cobalt base X-40 alloys the size of the primary solid particles in the Rheocast slurries is close to that of primary dendrite arm spacings obtained at equivalent cooling rates.

High speed motion pictures taken during mold filling of various viscosity fluids in the transparent die casting machine show that transition from spray filling to a solid front fill, at equivalent

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gate velocities, is accomplished by increasing the kinematic viscosity of the charge material. The general aim of these studies is to establish the optimum process parameters (gate and vent geometries and location, velocity, etc.) for machine casting of high quality components.

Microsegregation patterns in Rheocast copper base alloy 905, cobalt base alloy X-40, 304 and 440C stainless steels were determined before and after homogenization heat treatments. A flat composition profile was noted within the primary solid particles of the as-Rheocast specimens. At the particle boundaries, compositions varied abruptly. A short (5 hrs.) high temperature (~1300°C) homogenization heat treatment alters the composition profiles significantly.

Tensile properties of as-Rheocast copper base alloy 905 were identical to the conventionally cast material. The compressive yield strength of as-Rheocast 440C stainless steel improved with increasing temperature of homogenization, reaching close to that of the wrought alloy after 5 hours at 1300°C.

In the economic analysis a cooperative effort was established with the U.S. Army Production Equipment Agency to identify parts presently procured by D.O.D. that would be amenable to manufacture by the new machine casting process. A model was developed for initial screening of the parts. The sequence of manufacturing operations in the machine casting process were identified and broken down into direct material and direct labor costs. A model was developed to estimate manufacturing costs by this new process.

I. INTRODUCTION

On October 1, 1975 work was initiated at the University of Illinois at Urbana-Champaign as part of a joint University-Industry research program on machine casting of ferrous alloys. At that time, the overall program had already been in effect for 33 months -- it was initiated in January, 1973. The initial members of the program were Massachusetts Institute of Technology, Abex, General Electric and Hitchiner Corporations. The overall aim of the program was to plan and test new and innovative processes and develop a machine casting system for ferrous alloys that would produce good quality parts economically and at high speed.

A variety of casting concepts were explored and reported by the participants. Of these only two processes have evolved that show the promise of fulfilling the initial objectives of the program. The first is a process developed at the Massachusetts Institute of Technology in which the charge material is partially solid with a special microstructure which lends itself to homogeneous deformation, hence casting of components in reusable molds. The two sub-processes that use a partially solid high temperature alloy charge have been designated as Rheocasting and Thixocasting. They have been described in detail in several reports and numerous publications (1-9). The second is application of the Hitchiner Corporation's CLA and CLV processes to casting of components using all liquid, as well as partially solid, charge material.

(a) A transparent model continuous slurry producer,

(b) A low-temperature alloy continuous slurry producer,

(c) A high-temperature alloy continuous slurry producer, and

(d) A laboratory casting machine which permits direct observation and photography of the mold filling characteristics of various viscosity fluids and low temperature liquid and partially solid slurries of alloys.

2. Work was carried out to determine the effect of cast (Rheocast) structure on homogenization heat treatment response and mechanical properties of high temperature alloys, copper base alloy 905, 440C and 304 stainless steel alloys, and X-40 cobalt base superalloy.

3. Economic Studies

(a) Work was initiated to identify parts presently procured by the Department of Defense that would be amenable to machine casting using the new machine casting process.

(b) Work was initiated to develop a cost breakdown for manufacturing of parts by the new machine casting process.

II. PROCESS VARIABLES IN THE CASTING SYSTEM

The basic design of the Rheocasting and Thixocasting systems has been described in detail in previous reports (1-3). The fundamental approach has been to produce a vigorously agitated, partially solidified charge material and to cast it either (i) directly into shape (Rheocasting) or (ii) into ingot molds for subsequent reheating to the partially solid state for shape casting (Thixocasting). In an effort to determine the effect of machine design and process parameters on the quality of the cast parts, both model and metallic casting systems were designed, constructed and operated. The casting system can be viewed as two separate operations:

(1) the continuous slurry producer, and

(2) the casting machine.

The understanding and control of heat and fluid flow in both the continuous slurry producer and the casting machine are essential for optimum performance of the system. Furthermore, heat and fluid flow during slurry production and the casting operation directly influence the structure, microsegregation and properties of the as-Rheocast structure and the internal soundness and properties of the subsequently cast shapes.

1. Process variables in the continuous slurry producer

These include:

(a) Shear Rate - which is a function of rotor geometry, the clearance between the rotor and the lower mixing chamber, and the rotation speed.

(b) Average Cooling Rate During Primary Solidification - which is a function of the thermal profile in the lower mixing chamber and the flow rate of the exiting

slurry (average residence time spent by the alloy in its solidification range), and

(c) Volume Fraction Solid - the volume fraction of primary spheroidal solid particles in the exiting slurry.

In a given continuous slurry producer these fundamental system parameters can be altered by changing the machine design and the operating variables (e.g. power input, cooling capacity, flow rate, etc.). The important process variables listed above combine to totally determine the microstructure, viscosity, and the rheological behavior of a partially solidified slurry. The structure of a slurry can be characterized by:

(a) the volume fraction of the primary solid particles,
(b) the size and distribution of size of the primary solid particles,
(c) the shape of and the amount of entrapped liquid in the primary solid particles, and
(d) the segregation profile of alloying elements in the primary solid particles.

In turn, the structure of a partially solidified, vigorously agitated, metal slurry influences its viscosity and rheological behavior (thixotropy), and the properties of the ingots and castings produced in important ways. A recent fundamental study on a low temperature alloy system has summarized the interrelationship of structure - viscosity - rheological behavior in metallic slurries (9). The basic understanding of this interrelationship is essential if the high viscosity and thixotropic behavior of metal slurries are to be fully exploited to produce internally sound parts in the shape casting process.

2. Process variables in the casting machine

Some experimental and theoretical work has already been carried out to determine the effect of casting partially solid high temperature metals on mold filling characteristics and mold thermal behavior (3). The process variables in the casting operation include the following:

(a) volume fraction solid in the charge material
(b) mold temperature
(c) mold fill time (before significant additional solidification occurs)
(d) gate and runner location and geometry
(e) location of overflows
(f) gate velocity, and
(g) pressure.

The relationship between these variables, metal flow and internal soundness of the parts should be determined if good castings of various geometries are to be successfully produced. It is to this end that the laboratory casting machine was designed and built to permit direct observation and high speed photography of fluid flow during mold filling of various viscosity fluids and low temperature liquid and partially solid alloy slurries.

III. DESIGN, CONSTRUCTION AND OPERATION OF VARIOUS CASTING SYSTEMS

Various model and high temperature continuous slurry producers and a transparent model die casting machine were designed, built and operated. A detailed description of these apparatuses, the operating procedures, and some of the findings to date are presented herein. Details of microstructures produced are presented in a separate section.

1. Transparent model continuous slurry producer

The transparent continuous slurry producer is made of glass to permit direct observation of fluid flow patterns in the upper (holding) and lower (mixing) chambers. A schematic and photograph of the transparent system are shown in Figures 1 and 2b respectively. Various viscosity fluids and solutions of NH_4Cl - H_2O are heated in the upper (holding) chamber via an immersion heater which is controlled by an automatic temperature controller monitored with a Chromel/Alumel thermocouple.

The lower (mixing) chamber is composed of two glass cylinders. The inner cylinder houses the mixing rotor and contains the viscous fluids or partially solidified, vigorously agitated, slurries of NH_4Cl - H_2O. The outer cylinder is a water cooling jacket that surrounds the lower (mixing) chamber enabling the establishment of a thermal gradient along the chamber length. In order to maintain continuous machine operation, a heated collection chamber is located below the exit port as shown in the schematic, Figure 1. Once re-

melted, the slurry is recirculated to the upper (holding) chamber via a pump. As with other slurry producers of this design, the flow rate of the material through the system (e.g. rate of slurry production) is altered by either raising or lowering the mixing rotor. Here, however, it is also necessary to control the flow of fluid through the pump with a manually operated valve located in the recirculation line.

The apparatus is operated continuously to conduct two distinct types of experiments.

1) NH_4Cl - H_2O is vigorously agitated during partial solidification in the lower (mixing) chamber in order to study the flow of primary solid particles and to establish the relationship between process variables and both slurry structure and the variation of volume fraction solid within the lower (mixing) chamber.
2) Clear, viscous fluids are continuously mixed and recirculated through the system. By injecting different color dyes into the lower (mixing) chamber, fluid flow patterns which develop in the upper and lower chamber can be analyzed.

The first group of experiments, conducted with NH_4Cl - H_2O material, have shown that upon partial solidification during mixing in the lower chamber, the solid forming has a particulate structure very similar to solid particles in Rheocast metal slurries. The structure of conventionally solidified and partially solidified (Rheocast) NH_4Cl - H_2O are compared in Figure 3.

Experiments are presently under way to relate the structure of the semi-solid slurry to the shear rate, cooling rate, and volume fraction solid during slurry production.

Flow instabilities (Taylor rings (10,11)) have been observed in the lower (mixing) chamber during the formation of NH_4Cl - H_2O semi-solid slurries. G. I. Taylor has shown that the flow of a fluid contained between concentric rotating cylinders becomes unstable when a certain Reynolds number of the flow is exceeded. The transition between laminar and turbulent flow, transition Reynolds number, is dependent on the ratio of the annulus thickness to the radius of the outer cylinder, the kinematic viscosity of the fluid and the rotation speed of the inner cylinder. In the continuous Rheocasting apparatus used in this study the occurrence of flow instabilities, which manifest themselves as high volume fraction solid rings, depends on the viscosity (volume fraction solid), shear rate, and rotor size and geometry. It has been determined that Taylor rings can form when a round rotor (grooved or ungrooved) is employed. However, the use of a rotor with a square cross section completely eliminates the flow instabilities. A comparison of the flow patterns formed during slurry production using a round and a square rotor is shown in Figure 4.

In the second group of experiments using different viscosity fluids and colored dyes, it has been shown that fluid flow patterns develop between the upper (holding) chamber and the lower (mixing) chamber. This type of fluid flow coupling enhances the convection of heat (and solute) thus reducing the effectiveness of external cooling during partial solidification. Corollary experiments conducted with the NH_4Cl - H_2O system indicate that the degree of coupling is reduced by (1) the presence of primary solid particles

in the mixing chamber, and (2) increasing the flow rate of the slurry through the mixing chamber.

2. <u>Low temperature alloy continuous slurry producer</u>

The low temperature alloy continuous slurry producer is employed to produce partially solid mixtures of Sn-Pb alloys. The apparatus shown in Figure 2a is functionally similar to both the transparent and high temperature slurry producers. The crucible is made of tubular stainless steel and contains two distinct regions, the upper (holding) chamber and the lower (mixing) chamber. The temperature of each chamber is individually controlled by automatically regulating the power and coolant inputs to a series of heating and cooling coils located along the crucible length. This control enables alteration of the thermal process parameter.

The upper chamber, functioning as a reservoir, is heated with a helical coil which is controlled to maintain the metal temperature above its liquidus. The lower mixing region is equipped with two pairs of heating coils each regulated by a proportioning time temperature controller. Depending upon the desired cooling rate during primary solidification in the lower (mixing) chamber, either air or water is passed through the copper cooling coils. During operation, the temperature gradient in the lower chamber is adjusted so that slurry exiting from the system contains the desired volume fraction of solid.

The mixing assembly, designed to provide vigorous agitation within the lower (mixing) chamber has been described in detail previously (1-3). Both square and round stainless steel rotors have

been used with the rotation speed controlled between 100 and 800 RPM. The flow of slurry through the system is controlled by adjusting the distance between the rotor bottom and the exit port valve seat. In order to replenish the top (holding) chamber during continuous operation, Sn-Pb stock can be added with a continuous feeding device.

In experiments conducted to date, the various process parameters have been varied to assess the effect of each upon the resulting structure and operability of the machine. Production rates have ranged from 2-10 lbs/minute. During these experiments continuous temperature measurements have been recorded from thermocouples located in both the top and lower chambers. The structural results will be presented in the next section. In a parallel effort, theoretical work has been initiated to develop an analytical predictive heat flow model for continuous slurry production based on the experimental observations in both the transparent model and low temperature alloy slurry producers.

3. <u>High temperature alloy continuous slurry producer</u>

Partially solid high temperature slurries are produced continuously by the machine shown in Figure 5. The crucible made from Vesuvius #235 (58% Al_2O_3, 26% C and 12% SiO_2) is composed of an upper (holding) chamber and a lower (mixing) chamber. The top chamber (3 5/8" diameter x 8" high) holds approximately 18 pounds of ferrous charge. The melt surface is protected from oxidation by a fire brick cover and an argon blanket. Also, the cover contains a hole through

which metal can be fed continuously to recharge the system. This reservoir is heated by induction with a 3KC, 50KW Brown Boveri motor generator set. The temperature of the top (holding) chamber is maintained above the liquidus and is monitored continuously with a Pt-Pt13%Rh thermocouple suspended in the melt.

The lower (mixing) chamber is cylindrical in shape (1 1/4" I.D. x 6" long). Two separate induction coils are wound around the outside of this chamber to provide both heating and cooling during operation. These two coils, upper and lower, are powered by a 20KW, 200KC ECCO high frequency power supply and a 2.5KW, 200 KC Lepel power supply, respectively. A 1/4" diameter exit port is located at the bottom end of the lower chamber. Also, four thermocouples are positioned along the outside length of the mixing chamber to provide a means of control for the various power input levels.

The mixing rotor is an 19" alumina closed end tube (1" O.D.) running concentrically to the bottom of the mixing chamber. Both square and round rotors are employed. The rotor is driven by a 3/4 H.P. D.C. motor capable of rotation speeds between 0-800 RPM. During operation, this rotation provides the necessary agitation within the lower chamber to generate the special Rheocast structure in the slurry. Flow of the slurry is controlled by either raising or lowering the mixing rotor. At its fully lowered position, the rotor rests on the exit port seat, thus stopping flow.

This apparatus has been used to produce partially solidified, vigorously agitated slurries of high temperature alloys under a number of different conditions wherein the process parameters

have been altered. The results of the structural and compositional analysis are presented in the next section.

4. Laboratory casting machine

A laboratory casting machine shown in Figures 6 and 7 was designed, constructed and operated. The unit, designed to simulate a commercial horizontal cold chamber die casting machine, consists of a split die, a locking mechanism, plunger and shot sleeve assembly, and a hydraulic power supply. The dies are fabricated from mild steel plate. One of the dies houses a flat ground quartz window as shown in Figure 7b. This assembly permits direct observation and high speed photography of the charge material as it flows through the gating system into the casting cavity. Fluid flow characteristics of various viscosity fluids and low temperature liquid and partially solid slurries of alloys are currently being studied. Two distinct casting cavity designs are used in these studies.

(a) A flat plate (4" x 4" x 1/8" thick) mold cavity was designed and machined into one half of the die. A schematic of the gating system (fan gates) is shown on the right side of Figure 6. A photograph of the gating system and the casting cavity, as seen through the quartz window half of the die, is shown in Figure 7b. This geometry is particularly suited for studies in which the effect of gate geometry and location, charge viscosity, and charge gate velocity on the fluid flow characteristic are to be determined.

(b) A simulated turbine blade casting cavity, having the exact dimensions as that used by Pratt and Whitney in this program,

has also been machined in a mild steel die. Results from work on this system will be sent to Pratt and Whitney so they can optimize their process parameters including the location and geometry of the gates, runners and vents in their system.

The shot piston (1 1/4" O.D.) is powered by a Reed Prentiss hydraulic system capable of 2000 psi pressure. This power supply has two accumulator tanks and automatic controls to regulate both injection pressure and speed. Metal injection velocities at the gate range from a few feet per second to that generally obtained on commercial die casting machines.

During operation, either controlled viscosity fluids or Sn-Pb alloys (liquid or semi-solid) are fed into the shot sleeve. During the casting of the low temperature alloys, the shot sleeve is heated by a controlled power supply. High speed motion pictures are taken during die fill using a 16 mm Fastex Movie Camera capable of film speeds at up to 7000 frames per second. The camera is activated by an automatic timer connected to a switch on the piston rod. A photograph of this assembly is shown in Figure 7a.

In experiments conducted to date, we have determined that the mode of die fill is sensitively dependent upon the viscosity of the charge material and the gate velocity. Figure 8 shows schematically two extreme types of metal flow into the die cavity. Of these two modes, spraying and stable front fill, it is postulated that the gentle fill pushing air ahead of the charge toward the air vents produces fewer laps and much less internal porosity. Actual observations using high speed motion pictures confirm this hypothe-

sis. Furthermore, it has been determined that the transition from spray filling to a solid front fill is accomplished by either decreasing the injection velocity or increasing the charge kinematic viscosity. These results are shown in Figure 9, wherein the charge viscosities accompanying solid front fill and spraying are 23.0 and 0.008 Stokes, respectively.

In future experimentation, the general aim is to expand this analysis to include additional process parameters such as gate and vent geometry and location. Through these combined efforts it is anticipated that guidelines can be established to determine the optimum process parameters for machine casting of high quality parts free of porosity and surface defects. Furthermore, analytical fluid flow models are being developed to complement the experimental studies and thus aid in predictive design.

IV. STRUCTURE, SEGREGATION, HOMOGENIZATION HEAT TREATMENT, AND MECHANICAL PROPERTIES OF RHEOCAST ALLOYS

A comprehensive investigation was initiated to characterize the structure, microsegregation, heat treatment response and mechanical properties of a variety of alloys cast from the partially solidified, vigorously agitated state. Initial results from these studies are presented below.

The various alloys studied included a Sn-15%Pb alloy (processed in the low temperature apparatus), copper base alloy 905, cobalt base alloy X-40, 440C stainless steel and 304 stainless steel. The chemical composition and the liquidus and solidus temperatures of the high temperature alloys are listed in Tables I and II. Work on the cobalt base Greek Ascoloy, one of the two alloys of interest to the Pratt and Whitney program, will be carried out in the next phase of this investigation.

1. Effect of Process Variables on Structure

As noted earlier, the three important process variables affecting structure during slurry production are shear rate, cooling rate, and volume fraction solid. Details of measurements of these three variables are discussed in the Appendix. The emphasis of the initial work carried out in this portion of the program was to study the effect of cooling rate during primary solidification on the primary solid particle size in the slurries. A Corollary experimental program was also carried out to determine the relationship between primary and secondary dendrite arm spacings and aver-

age cooling rate in the alloys cast from above their liquidus temperatures.

Previous experimental evidence (12), also confirmed in this work, indicates that dendrite arm spacing in a given alloy cast from above its liquidus temperature is influenced only by the average cooling rate or local solidification time. Generally, segregate spacing is found to be inversely proportional to average cooling rate to an exponent (or directly proportional to local solidification time to the same exponent). The relationship for a given alloy is:

$$d = at_f^n = b(\varepsilon_{Ave})^{-n} \tag{1}$$

where d is dendrite arm spacing, a, b and exponent n are constants (different constants for primary and secondary dendrite arm spacing), t_f is local solidification time, and ε_{Ave} is average cooling rate.

The relationship between average cooling rate, ε_{Ave}, and local solidification time, t_f, in conventionally solidified alloys and during primary solidification in a continuous slurry producer are discussed in the Appendix.

Figure 10 shows the data obtained to date on the low temperature model system. First the effect of a range of cooling rates, 0.001 to 50°C/sec, on the primary and secondary dendrite arm spacings of conventionally solidified Sn-15%Pb alloy was determined.

The linear relationship obtained on the log-log plot of segregate spacings versus average cooling rate confirms the relationship in equation (1). Superimposed on this plot is data obtained using the low temperature continuous slurry producer. The primary particle size, p.p.s., also decreases with increasing average cooling rate in the mixing chamber during slurry production. Furthermore, the size of the primary solid particles is close to that of primary dendrite arm spacings obtained at equivalent cooling rates. This observation is in line with our studies on the formation of Rheocast structures in the NH_4Cl - H_2O system. Solidification, during vigorous agitation, in this transparent system starts with formation of discrete primary dendrite stocks with a few secondary arms attached to each stock. As solidification proceeds secondary arms remelt, break off, and coarsen. At the same time different particles have a tendency to weld and fuse together. Increasing the cooling rate at the beginning of solidification at equivalent shear rates, results in smaller dendrites and smaller spheroidal primary solid particles in the slurry. A representative microstructure of water quenched Sn-15%Pb alloy slurry is shown in Figure 11.

Figure 12 shows the same type of data generated in this work for the cobalt base alloy X-40. Again, the linear plots of segregate spacings versus cooling rate confirm the relationship in equation (1). The data point shown in Figure 12 for the measured primary solid particle size in the continuously produced slurry of

the alloy is close to the primary dendrite arm spacing. Figure 13 shows representative microstructures of conventionally solidified and Rheocast (water quenched) cobalt base alloy X-40 and 440C stainless steel. Work is presently underway to generate the same type of data in selected high temperature alloy systems as that presented for the model Sn-15%Pb alloy in Figure 10. The present design of the high temperature continuous slurry producer is such that the maximum average cooling rate in the mixing chamber is approximately 1.0°C/sec. Both experimental and theoretical work should be carried out to increase the average cooling rate (reduce the primary particle size) in this apparatus.

The two other process variables affecting the structure of partially solidified, vigorously agitated metal slurries are volume fraction solid and shear rate. Initial experiments on the Sn-15%Pb alloy indicate that primary solid particle size increases with increasing volume fraction solid. On the other hand, shear rate affects the geometry of the primary solid particles in important ways. Earlier work (9), confirmed in our studies on the low temperature continuous slurry producer, has shown that the amount of entrapped liquid in the primary solid particles increases as the shear rate is reduced. The effect of this entrapped liquid is tantamount to an increase in the effective volume fraction of solid in the slurry and results in a corresponding increase in viscosity (9).

Full exploitation of the special rheological properties of vigorously agitated, partially solidified metal slurries in the

machine casting process will require a better understanding of (i) the various mechanisms responsible for the formation of the structures, and (ii) the influence of process variables and the physical-chemical properties of the alloy systems on these mechanisms, hence the structure and rheological properties of the slurries. The work in this portion of the program which is directed toward this goal is continuing.

2. Segregation, Homogenization Heat Treatment and Mechanical Properties

The high temperature alloys listed in Table I (with the exception of cobalt base Greek Ascoloy) were subjected to different homogenization heat treatments and their microsegregation patterns were compared to the as-Rheocast specimens. Initial work was carried out to determine the mechanical properties of two of the alloys.

(a) Segregation and Homogenization Heat Treatment Studies

A series of Rheocast (water quenched) high temperature alloys were homogenization heat treated over the temperature range of 770°C to 1300°C for periods of 5 to 100 hrs. Table III lists the various heat treatment times for each alloy. These high temperature heat treatments were carried out in a Brew 300 - MC vacuum furnace at 0.04 microns ($4x10^{-5}$ torr) pressure. The electron microprobe technique was used to study the microsegregation patterns of the as-Rheocast and heat treated specimens.

Representative solute distributions in the primary solid particles and the quenched liquid matrix of as-Rheocast cobalt base

alloy X-40 and 304 stainless steel are shown in Figures 14 and 15. The results clearly show a flat composition profile within the primary solid particles. At the particle boundaries the compositions vary abruptly. The composition profile in the X-40 alloy after five hours of homogenization at 1300°C is shown in Figure 16. The duplex Rheocast (water quenched) structure has been completely eliminated. The matrix concentration of Cr and Ni has increased with a corresponding decrease in W.

The as-Rheocast 440C stainless steel showed a similar structure with enrichment of chromium and molybdenum at the primary solid particle boundaries. The composition profile of this alloy after five hours of homogenization at 1300°C is shown in Figure 17. Again, the duplex Rheocast (water quenched) structure has been eliminated. The solid phase forming during primary solidification is austenite which results in carbon enrichment of the remaining liquid. Near the end of solidification a eutectic reaction takes place with precipitation of cellular appearing M_7C_3 carbides. During high temperature homogenization heat treatment the carbides identified as $(Cr,Fe)_7C_3$ are transformed to $(Cr,Fe,Mo)_{26}C_6$ carbides (14).

(b) <u>Mechanical Properties</u>

Ingots of Rheocast (slowly cooled) copper base alloy 905 and 440C stainless steel were machined into test specimens and their mechanical properties were measured in the as-cast and homogenization heat treated conditions. Due to the lower cooling rates achieved in the fiberfrax coated molds the structure of the 1 1/4" diameter ingots does not show the typical duplex structure of water

quenched slurries. The primary solid particles coarsen during solidification in the ingot mold resulting in an equiaxed grain structure. For example, the as-cast structure of 440C stainless steel ingots is identical to the heat treated specimen shown in Figure 17.

The tensile properties of copper base alloy 905 ingots in the as-cast and homogenization heat treated conditions are listed in Table IV. For comparison, the reported properties of the conventionally cast alloy are also listed. There is no significant difference between the three sets of properties.

Rheocast ingots of 440C stainless steel were homogenized at 1100°C to 1300°C for times of up to 20 hours. Compression test specimens from these ingots were subjected to standard 440C alloy quench and temper heat treatment. The specimens were tested at different temperatures up to 600°C. It was found that 0.2 percent offset yield strength improved with increasing time and temperature of homogenization heat treatment, Figure 18. For example, the room temperature yield strength of the as-Rheocast material was approximately 150,000 psi. After five hours at 1300°C, the measured yield strength increased to approximately 240,000 psi. This value is close to the 270,000 psi reported for wrought 440C (16).

Improvement in the strength of the as-Rheocast alloy with homogenization heat treatment has been shown to be a direct consequence of transformation of the grain boundary M_7C_3 carbides to $M_{23}C_6$ carbides. This conversion is accompanied by the diffusion of carbon and homogeneous distribution of the latter carbides within the grains of the alloy (14).

Both the homogenization heat treatment studies and the mechanical property measurements are continuing. The ultimate aim is to develop the necessary homogenization heat treatment response of specific high temperature Rheocast alloys and relate the microsegregation pattern modifications to mechanical properties.

V. ECONOMIC STUDIES

The general aim of this portion of the program is to evaluate the economics of the ferrous machine casting process (Thixocasting) and develop a model to project and compare cost per part with established methods of manufacture. In the first six months of this investigation work was initiated:

(1) to identify parts presently procured by the Department of Defense that would be amenable to machine casting using the Thixocasting process,

(2) to develop a cost breakdown for manufacturing of parts by the new machine casting process.

Before proceeding with the economic studies, it is appropriate to review some of the important inputs in the cost analysis of the new machine casting process which are technical in nature. These include:

(i) life of machine components, especially die life.

(ii) quality of the cast parts, including mechanical properties.

Direct die temperature measurements have shown that thermal shock to the die is significantly reduced when a partially solidified charge material is used as opposed to a conventional liquid metal charge (3). However, the projected improvements in die life, as well as other machine components (shot sleeve and plunger) have yet to be determined in a pilot plant operation.* It has further

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*A pilot plant machine casting operation for Thixocasting of stainless steel alloys is presently underway at M.I.T. as part of this program. It is anticipated that actual measured die lives will become available for inclusion in the economic study before the completion of the program.

been demonstrated that due to the high viscosity of the partially solidified slurries, reduced turbulence during die fill, the quality of the parts (casting soundness) is superior to parts machine cast using a liquid metal charge. However, acceptance of the machine casting process over alternate manufacturing techniques of ferrous alloys is dependent on the demonstration that mechanical properties of the parts will meet the required specifications. Work on structure-property relationships has been initiated in this study as reported in the earlier sections. Finally, as will be shown in the initial economic analysis herein, a major advantage of machine casting over alternate manufacturing techniques (e.g. investment casting, forging, etc.) would be the machining cost saved in producing parts to net or near-net shape in a single operation. The potential use of sliding or disposable cores in the machine casting of ferrous alloys has yet to be demonstrated.

1. Identification of Parts

A survey was initiated to identify parts presently procured by the Department of Defense that would lend themselves to fabrication by the new machine casting process. Requests for assistance were forwarded to the Air Force Materials Laboratory at Wright-Patterson and the Office of the Assistant Secretary of Defense for Installations and Logistics. The latter request resulted in the initiation of a cooperative effort between the U.S. Army Production Equipment Agency and the University of Illinois to survey parts presently procured by the Army.

A number of criteria were developed to permit initial screening of the parts. These include:

(a) Material - steels (especially stainless steels) and cobalt base superalloys.

(b) Weight - parts to weigh 5 lbs. or less. Initially, parts weighing less than 2 lbs. would be considered.

(c) Number of parts - high volume parts, 10,000 or more.

(d) Thinnest section - 60 mills or more, prefer 1/16" minimum section thickness.

(e) Cores - no blind cores.

(f) Machining - present manufacturing techniques should require a significant amount of machining - at least 50% of cost incurred is for machining.

A second list was compiled to identify the necessary information on selected parts for cost analysis.

(a) Alloy composition

(b) Mechanical drawing, and actual part (if available)

(c) Quantities to be produced (projected)

(d) Property specifications

(e) Heat treatment requirements

(f) Current or past manufacturing processes

(g) Name of manufacturer

(h) Cost breakdown

In addition to the cooperative effort established with the U.S. Army Production Equipment Agency, a few manufacturers of parts for the Department of Defense were contacted directly. One of the in-

dustrial participants of this program, Hitchiner Manufacturing Company, provided mechanical drawings and initial cost breakdown for several parts that they investment cast for the Department of Defense.

Two of the several parts identified by Hitchiner Manufacturing Company are listed below. The associated cost breakdown for investment casting and machining of these parts is available.

Hammer, M-16 Rifle

This component has been selected for machine casting in the pilot plant operation presently underway at M.I.T. Photographs of the investment cast part, which is identical to the presently machine cast part, are shown on the left side of Figure 19. The mechanical drawing of the casting showing exact dimensions, tolerances, alloy composition, inspection and heat treatment is shown in Figure 20. The total cost to investment cast and machine the part, including overhead, is approximately $2/part. This total cost is almost evenly split between the casting-inspection and the machining halves of the manufacturing operations.

Channel-Trigger, M-60 Machine Gun

Photographs of the as-cast (investment) part are shown in Figure 21.

2. Cost Breakdown - New Machine Casting Process

Cost associated with the manufacture of parts by the new machine casting process (Thixocasting) is subdivided into specific sequence of operations:

(a) Die design, tooling and set-up*;

(b) Melting and Rheocasting - billets produced are of appropriate diameter to fit in the shot sleeve of the casting machine;

(c) Ingots are cut to appropriate lengths for machine casting**;

(d) Reheating to liquid plus solid temperature range and machine casting;

(e) Castings are cut off the runners and biscuit;

(f) Rough Inspection;

(g) Heat Treatment - if required in specifications;

(h) Machining and finishing;

(i) Magnaflux/Zyglo inspection - if required in specifications;

(j) X-ray - if required in specifications;

(k) Certification - chemical and/or mechanical - if required in specifications.

The sequence of manufacturing operations is broken down in direct material and direct labor costs. Some of the usual manufacturing overhead costs (e.g., utilities, service and maintenance, employees benefits) are considered part of the direct material and direct labor costs. The other manufacturing overhead costs (e.g. administration, marketing, research, sales, profits, etc.) are

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*Die maintenance cost per Piece will be considered in the die tooling cost--of course, total die life would be an important item in cost per piece.

**In a continuous production operation the slurry producer could be combined with a continuous casting machine. The emerging billets could then be cut to the appropriate lengths in a single operation in phase with the casting rate.

unique to the manufacturer, hence are not included in this or alternate manufacturing cost analysis. Direct materials and labor costs incurred in the sequence of operations (a) through (d) are estimated from the work sheets for:

Estimated Rheocast Metal Cost

Estimated Metal Cost per Piece

Estimated Reheating and Die Casting Cost

Details of these work sheets are shown in the following pages.

The cost of capital equipment is included by calculating the amortized capital equipment cost from Table V.

$$\text{Amortized Capital Equipment Cost/Piece} = \frac{\$16{,}500.00}{\text{\# of pieces to be made per year}}$$

Work Sheet - Estimated Rheocast Metal Cost

Alloy Cost/lb. + (Melting Cost + Rheocasting Cost)/lb =

__________ + (__________ + ________________ =

Rheocast Metal Cost/lb.

__________________.

Melting Cost in an investment foundry using a 500 lb. induction furnace is approximately 10¢ lb. This figure includes labor and overhead, furnace linings, melt losses, etc.

Rheocasting Cost includes the additional cost of special crucibles, rotors, thermocouples, etc. Assuming simultaneous melting and Rheocasting (as in a continuous slurry producer) at a casting rate of approximately 500 lbs/hr, the estimated cost for Rheocasting would add approximately 4¢/lb. to the above melting cost.

Work Sheet - Estimated Metal Cost per Piece

A. Net Metal Cost per Shot

Pieces/Die x lbs/Piece + lbs/G,R,B,&O* =

________ x ________ + ________ =

lbs/shot x Rheocast Metal Cost/lb = Gross Cost - lbsx(G,R,B,&O) x Scrap Price

________ x ________ = ________ - ________ x ________

= Net Cost

= ________

B. Net Metal Cost per Piece

Net Cost ÷ Pieces/Die = Net Cost/Piece

________ ÷ ________ = ________

* G,R,B,&O designate gates, runners, biscuit and overflows.

Work Sheet - Reheating and Casting Cost per Piece

Labor (fringe + utilities) ÷ (Shots/hr x Pieces/die)

____________ ÷ (______ x ______)

+ Die Cost/Piece + Shot Sleeve Cost/Piece + Plunger Tip Cost/Piece

+ ______ + ________ + ________

+ Lubricant Cost/Shot ÷ Pieces/die = Cost/Piece

+ ________ ÷ ______ = ______

Shots/hr would include die set-up time.

Die cost includes the total cost for design and fabrication of the die and die maintenance cost for the duration of die life. Assuming that a given die has multiple casting cavities, then

$$\text{Die Cost/Piece} = \frac{\text{total die cost}}{\text{pieces/die} \times \text{die life}}$$

$$\text{Shot Sleeve Cost/Piece} = \frac{\text{cost of shot sleeve}}{\text{pieces/die} \times \text{shot sleeve life}}$$

VI. CONCLUSIONS

1. Various model and high temperature continuous slurry producers and a transparent model die casting machine were designed, built and operated.

2. The structures of Rheocast slurries of a non-metal, NH_4Cl-H_2O, and a variety of metallic alloys including Sn-15%Pb, copper-base alloy 905, cobalt base alloy X-40, 440C and 304 stainless steels were studied.

3. In general, primary solid particle size in the slurries decreased with increasing cooling rate during solidification. In the Sn-15%Pb and cobalt base alloy X-40 the size of the primary solid particles in the Rheocast slurries is close to that of primary dendrite arm spacings obtained at equivalent cooling rates.

4. Solute distribution profiles in as-Rheocast structures can be altered by short time homogenization heat treatment at high temperatures. The heat treatment affected the yield strength of 440C stainless steel favorably. The room temperature compressive yield strength of the alloy increased from 150,000 psi to 240,000 psi after a 5 hour homogenization at 1300°C.

5. The transparent laboratory die casting machine permits direct observation and high speed photographyof fluid flow during die filling. Initial studies have verified the need for a comprehensive study to identify the optimum conditions (e.g. gate and vent geometries and locations, gate velocity, pressure, etc.) necessary to cast high quality components in the machine casting sequence of the process.

6. An economic study was initiated to evaluate the economics of the ferrous machine casting process (Thixocasting). Initial work

was carried out to identify a variety of components that could be manufactured by this process.

7. A model was developed to permit cost breakdown for manufacture of parts by the new machine casting process. An important unknown in this analysis is the life of machine components. Work is presently underway elsewhere in this program to establish die and other machine component lives.

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APPENDIX

The methods of measurement of the three important process variables during production of partially solidified, vigorously agitated, metal slurries are described below.

(a) Shear Rate - Average shear rate in the annulus in the mixing chamber is calculated from the following equation:

$$\gamma_{Ave} = \frac{2\Omega_o}{(1-\kappa^2)} \kappa \qquad \text{(A-1)}$$

where κ is the ratio of the radius of a round rotor (or equivalent radius of a square rotor) to the radius of the mixing chamber (13), and Ωo is angular velocity. In experiments carried out to date in both the low and high temperature continuous slurry producers, shear rates calculated using equation (A-1) were in the range of 400 to 700 sec^{-1}.

(b) Average Cooling Rate - This is the average cooling rate experienced by the alloy in its solidification range during primary solidification. In a conventionally cast alloy (alloy completely solidified from above its liquidus temperature) the average cooling rate is obtained from the following equation:

$$\varepsilon_{Ave} = \frac{\Delta T_s}{t_f} \qquad \text{(A-2)}$$

where ΔT_s is the temperature range of solidification (liquidus minus solidus temperature) and t_f is local solidification time.

Average cooling rate experienced by an alloy in the mixing chamber during primary solidification of a slurry is now defined as:

$$\varepsilon_{Ave}(g_s) = \frac{\Delta T_s(g_s)}{t_f(g_s)} \qquad \text{(A-3)}$$

where g_s is the volume fraction of primary solid particles in the slurry, $\Delta T_s(g_s)$ is the difference between the liquidus temperature and the temperature of the exiting slurry, $t_f(g_s)$ is the average residence time of the alloy in the mixing chamber (between the exit port and the height in the mixing chamber where the alloy reaches its liquidus temperature).

In the low temperature continuous slurry producer, thermocouples are located directly in the mixing chamber (through the side walls). Therefore, $t_r(g_s)$ and $\Delta T(g_s)$ in equation A-3 are directly calculated from flow rate measurements (rate of slurry production) and the recorded temperature profile in the lower (mixing) chamber. g_s is calculated from the Scheil equation and the phase diagram of the binary Sn-Pb alloy. Average cooling rate during primary solidification is then calculated from equation A-3.

In the high temperature system the thermocouples are located on the outside wall of the crucible. The location of the liquidus temperature in the mixing chamber is calculated by assuming a constant rate of heat extraction per unit length in the upper portion of the mixing chamber. Average residence time, $t_r(g_s)$ is again calculated by combining the information from above with measured flow rates. $\Delta T_s(g_s)$ is determined by (i) locating a thermocouple in the direct path of the exiting slurry, and (ii) first measuring the volume fraction solid in water quenched drops of the slurry by quan-

titative metallographic techniques and coupling this information to an experimentally predetermined curve relating volume fraction solid to temperature in the solidification range of each specific alloy.

(c) Volume Fraction Solid - Volume fraction solid in a slurry is determined as described above. Quantitative metallography is always carried out on samples that are directly water quenched as they exit from the continuous slurry producer. Since the remaining liquid in the slurry is rapidly solidified without experiencing shear, it exhibits a fine dendritic structure and delineates the spheroidal (non-dendritic) primary solid particles.

TABLE I

Composition of High Temperature Rheocast Alloys

ALLOY	ELEMENTAL COMPOSITION IN WT·%											
	C	Co	Cu	Cr	Fe	Mn	Mo	Ni	Si	Sn	W	Zn
1. Copper Base Alloy 905	-	-	Bal	-	-	-	-	-	-	10	-	2
2. Cobalt Base Alloy X-40	0.5	Bal	-	26.5	-	-	-	10.7	-	-	7.2	-
3. Cobalt Base Greek Ascoloy	0.18	Bal	-	12.5	-	-	-	2.2	-	-	3.3	-
4. 440C Stainless Steel	0.6	-	-	17	Bal	1	-	-	1	-	-	-
5. 304 Stainless Steel	0.08	-	-	19	Bal	-	-	9	-	-	-	-

TABLE II

Solidification Range of Rheocast Alloys

ALLOY	LIQUIDUS (^oC)	SOLIDUS (^oC)
1. Copper Base Alloy 905	1000	855
2. Cobalt Base Alloy X-40	1433	1349
3. Cobalt Base Greek Ascoloy	1490	1383
4. 440C Stainless Steel	1510	1370
5. 304 Stainless Steel	1455	1400

TABLE III

Homogenization Heat Treatment Times and Temperatures
of Rheocast Alloys

ALLOY	TEMPERATURE (°C)	TIME (Hrs)
Copper Base Alloy 905	770	5 and 20
Cobalt Base Alloy X-40	1100	5, 20 and 100
	1200	"
	1300	"
440C Stainless Steel	1100	5, 20 and 100
	1200	"
	1300	"
304 Stainless Steel	1100	5, 20 and 100
	1200	"
	1300	"

TABLE IV

Mechanical Properties of Copper Base Alloy 905

	YS (KSI)	UTS (KSI)	% Elongation
As Rheocast	19	47	30
Rheocast and Homogenized at 770°C for 20 hours	22.6	44.3	23
Conventional Dendritic Alloy*	22	45	25

*Typical mechanical properties of commercial conventionally cast 905 alloy reported in Reference 15.

Table V

CAPITAL EQUIPMENT COST FOR PILOT PLANT MACHINE CASTING OPERATION

Description	Purchase Price and Installation($)	Write-Off Period(Years)	Annual Depreciation ($/year)
One 100 KW and one 50 KW induction power supply for Rheocasting	54,000.00	15	3,600.00
Continuous Rheocasting Machine	20,000.00	10	2,000.00
One 50 KW induction power supply for slug reheating	26,000.00	15	1,733.33
Instrumentation for Rheocasting and Machine (die) Casting	25,000.00	10	2,500.00
400 ton die casting machine	80,000.00	12	6,666.66
TOTAL	$205,000.00		$16,500.00

The equipment needed for pilot plant manufacturing of ferrous parts using the machine casting (Thixocast) process include the following:

(i) A continuous slurry producer including two induction power supplies (one each for the upper holding and lower mixing chambers).
(ii) A slug reheating furnace (induction coils and softness tester) and an induction power supply.
(iii) Instrumentation; multi-channel temperature recorder, visicorder and associated equipment.
(iv) Die Casting Machine.
(v) Trimming press (or cut-off wheel), machining and finishing equipment normally used in an investment foundry or a low temperature metal die casting operation.

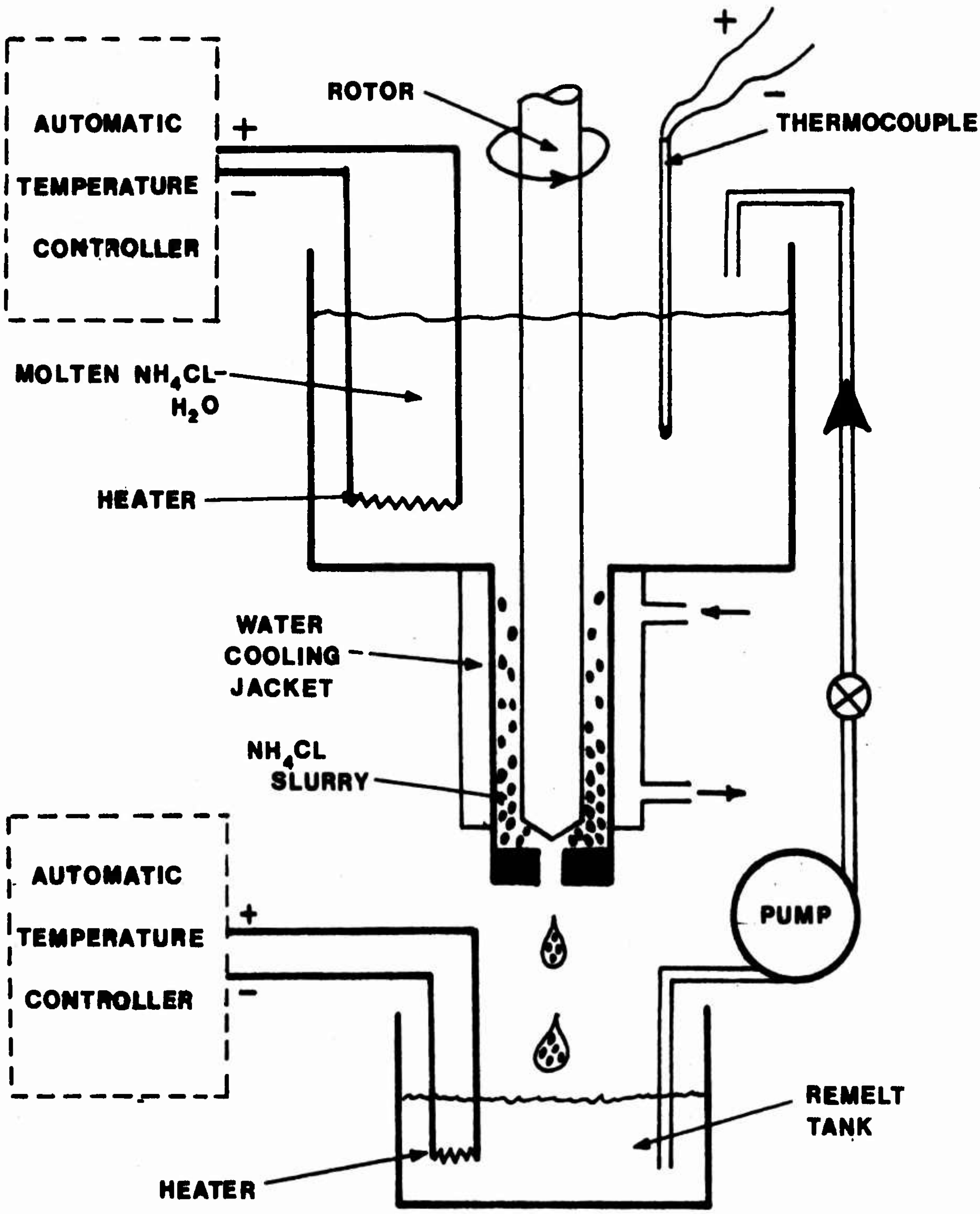
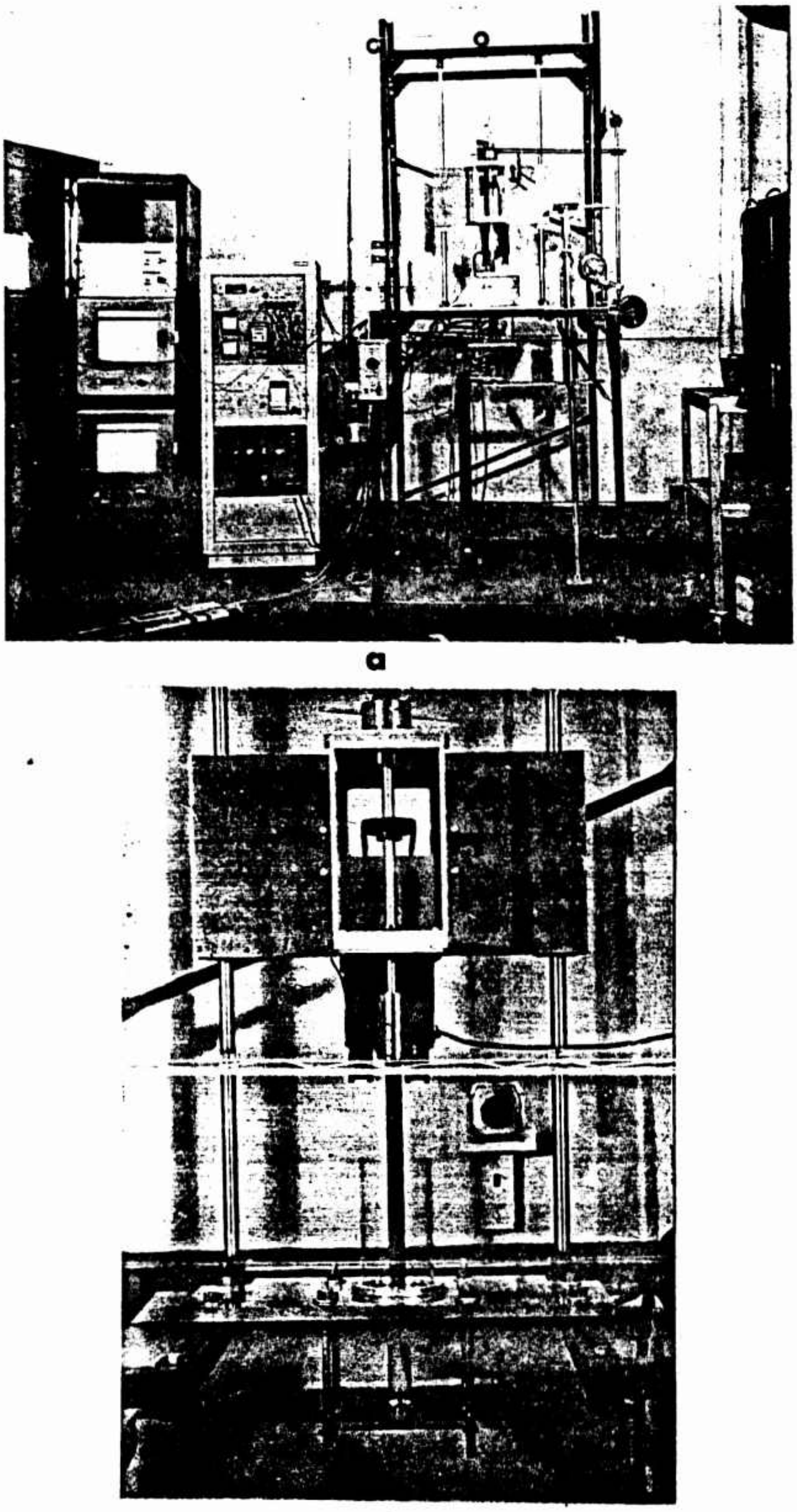


Figure 1 . Schematic diagram of the transparent Rheocasting machine and recirculation system used to continuously produce NH_4Cl - H_2O semi-solid slurries.



a

b

Figure 2 . Photographs of the low temperature model continuous slurry producers. Top: overall view of the machine used to produce semi-solid Sn - Pb alloys. Bottom: close view of the transparent assembly used to study the continuous production of NH_4Cl - H_2O semi-solid slurries.

Figure 3. Comparison of conventionally cast dendrite (top) and Rheocast (bottom) microstructures of NH_4Cl - H_2O. Magnification 100X.

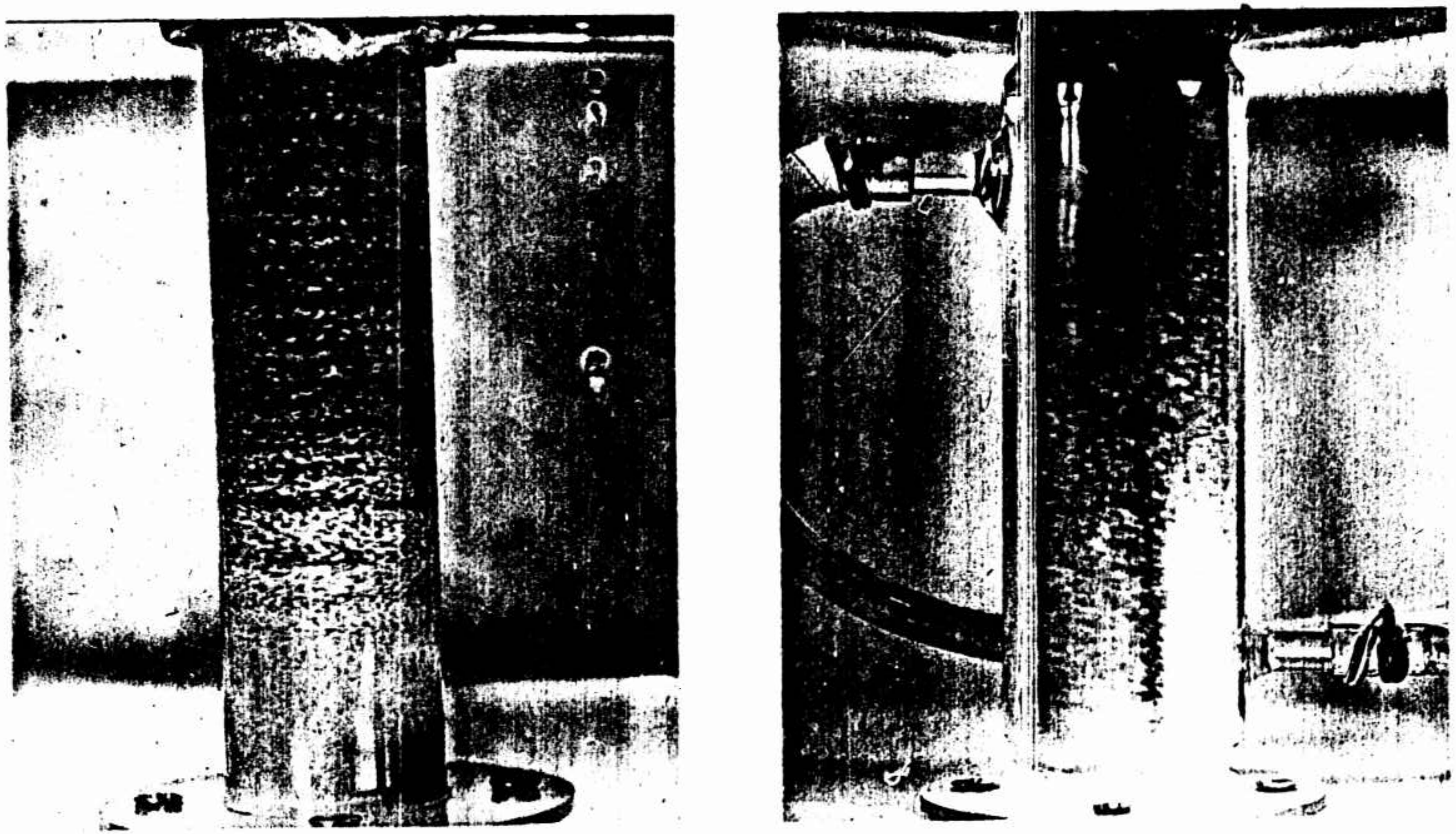
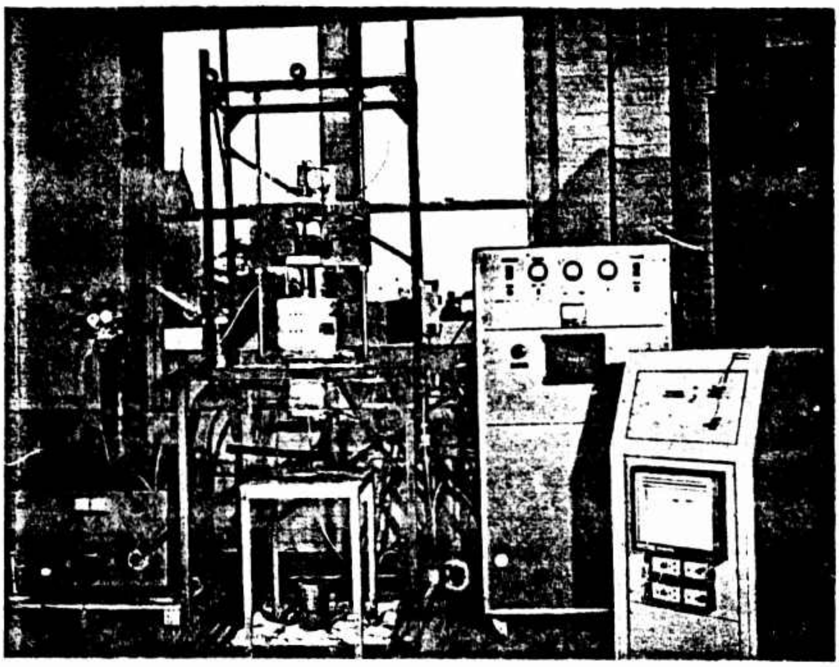
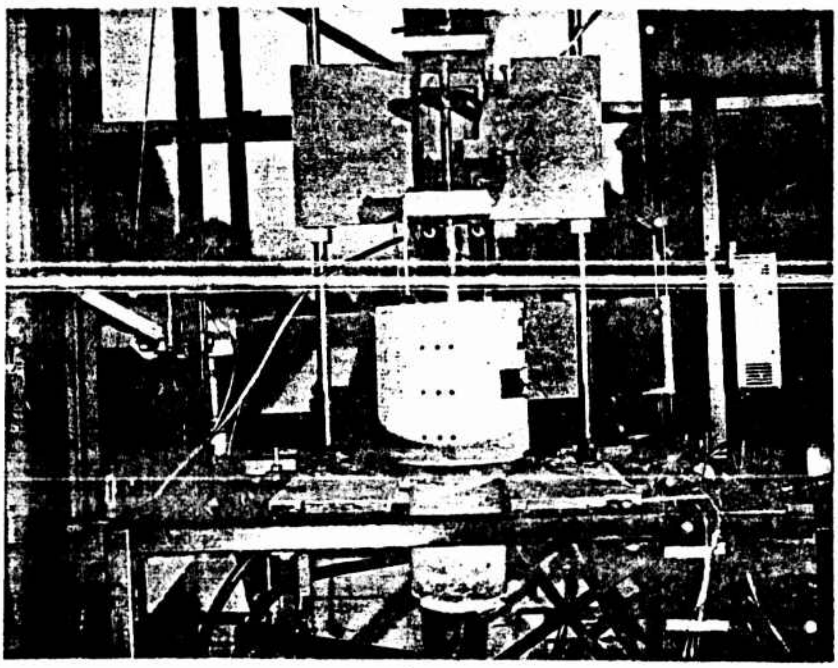


Figure 4. Photographs of lower mixing tube of the transparent Rheocaster taken during the production of NH_4Cl - H_2O semi-solid slurries White regions correspond to solid NH_4Cl particles. Left: round rotor. Right: square rotor.



a



b

Figure 5. Photographs of the continuous high temperature slurry producer. Top: overall view showing power supplies, recorder, and slurry producer. Bottom: close view of the Rheocasting furnace and rotation assembly.

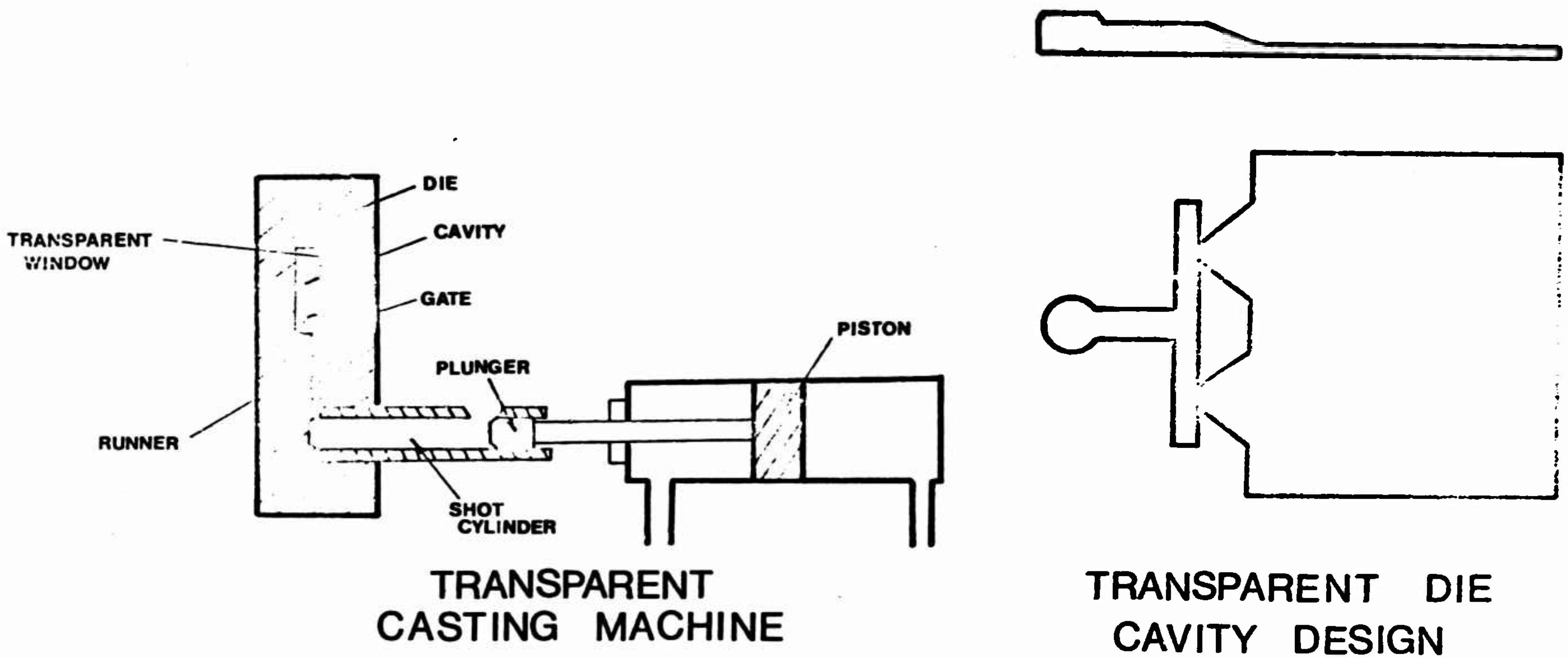
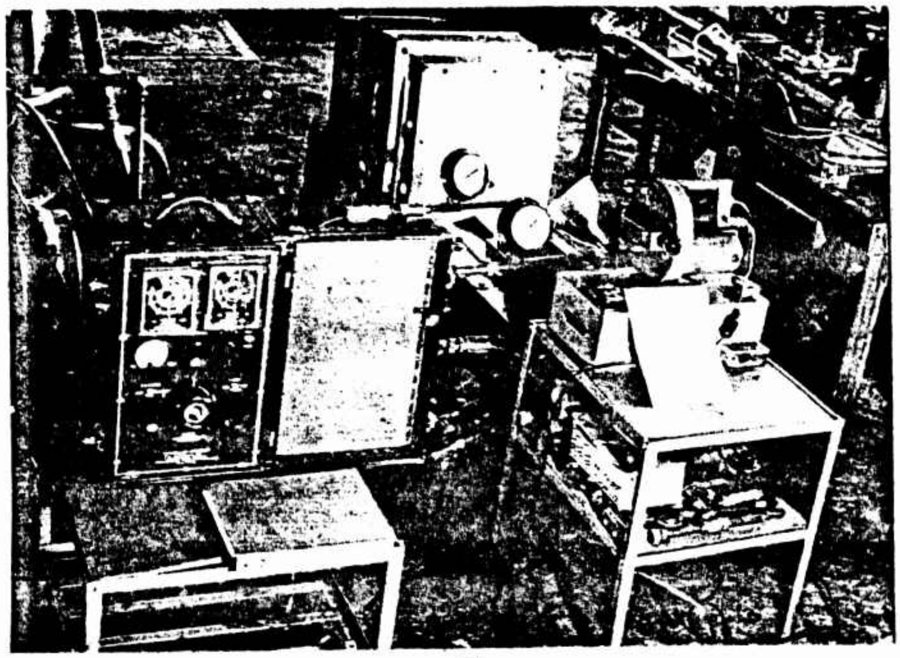


Figure 6. Schematic diagrams of the transparent casting machine. Left: overall view showing die and injection assembly. Right: view showing cavity design



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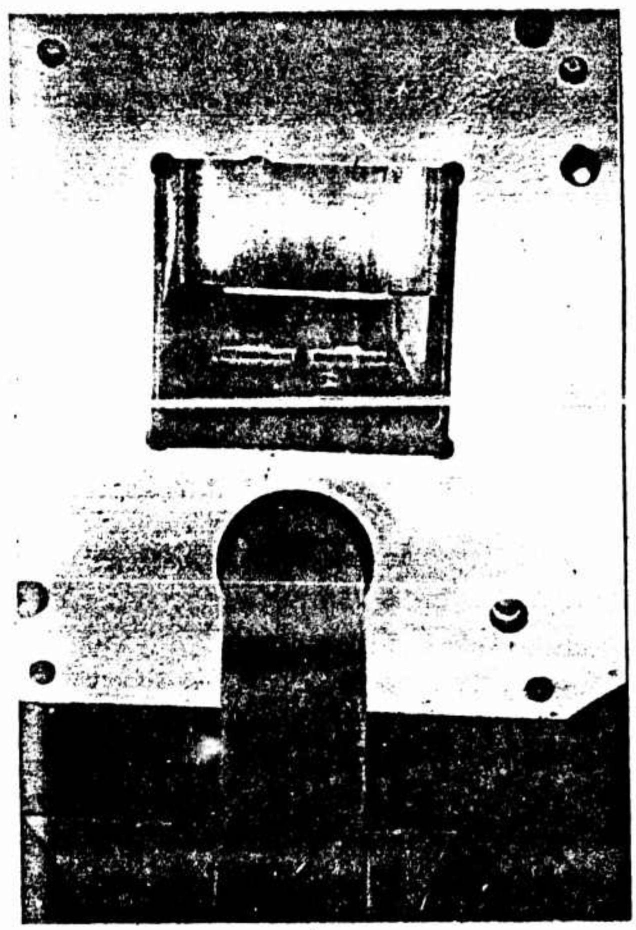


b

Figure 7 Photographs of the transparent casting machine used to study the die filling behavior of low temperature liquids and semi-solid mixtures Top: overall view including casting machine, high speed movie camera, and power supply. Bottom: close view showing cavity design, transparent window and shot sleeve.

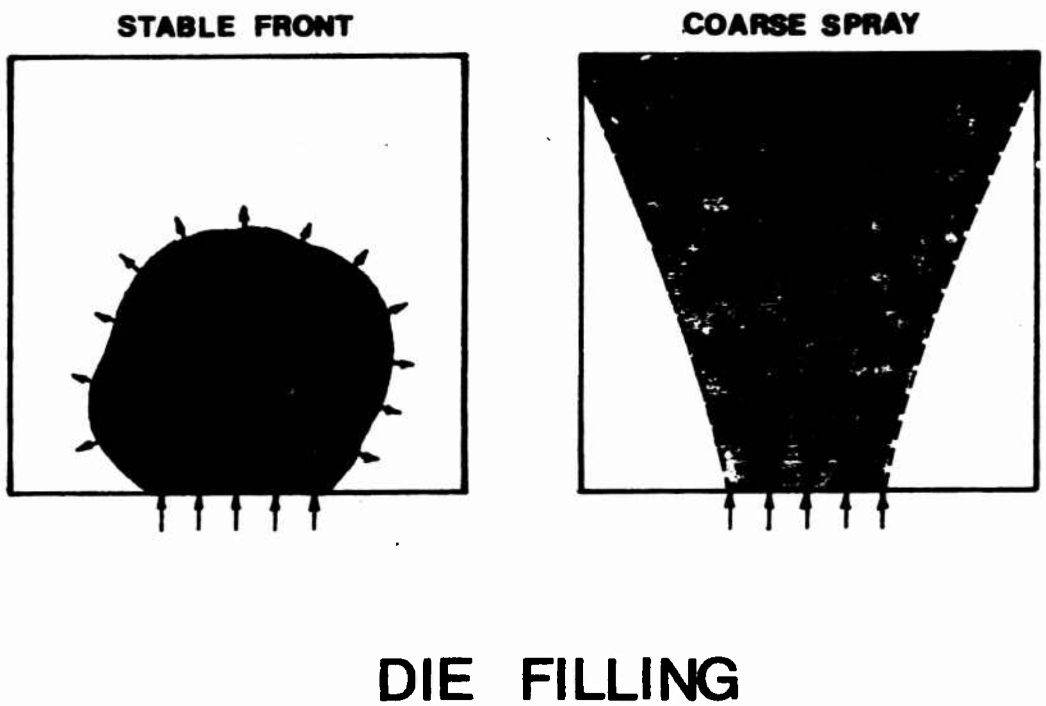


Figure 8 . Die filling patterns observed in the transparent casting machine. Left: solid front fill during the casting of a high viscosity liquid. Right: coarse spray during the casting of a low viscosity liquid.

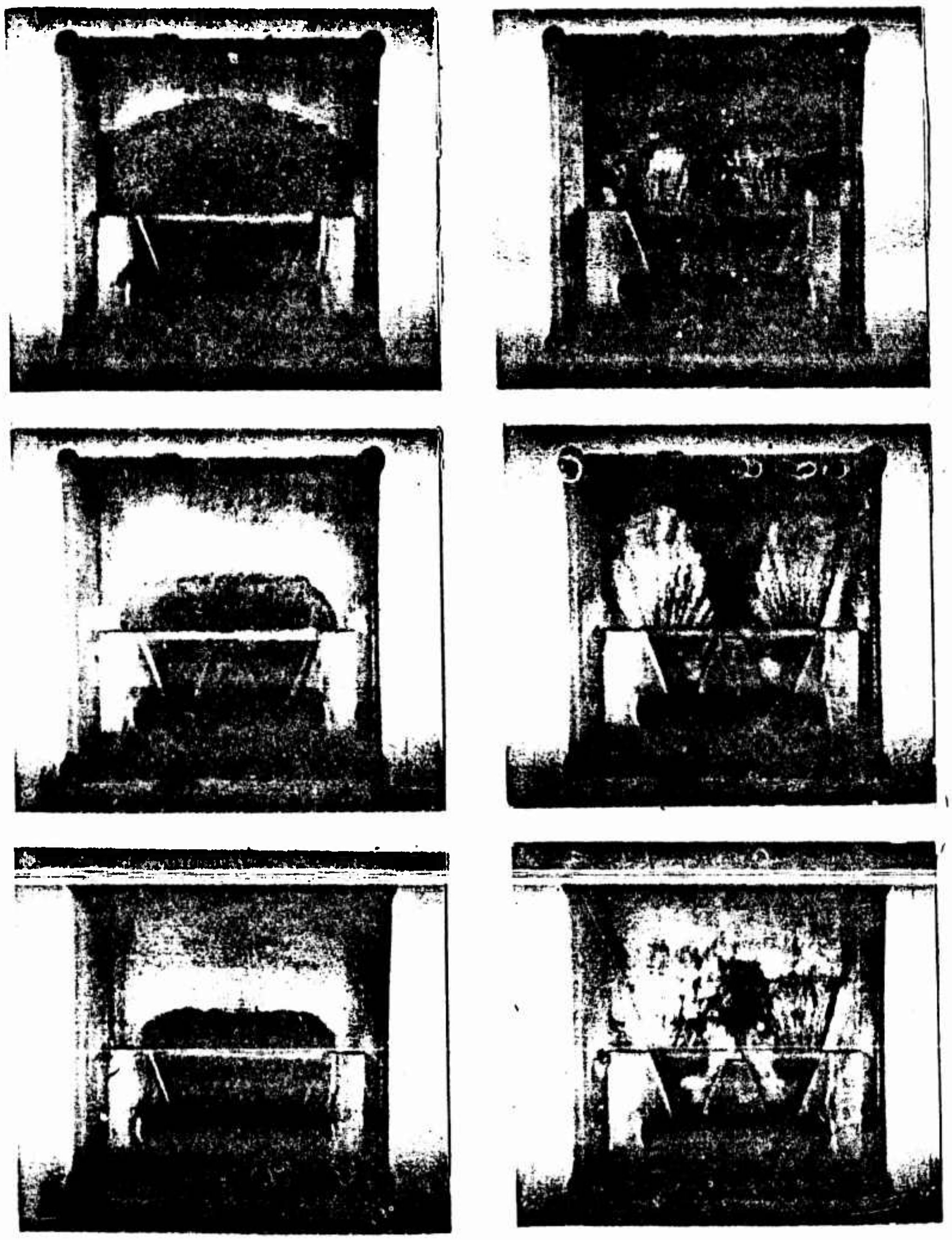


Figure 9. Sequence of pictures taken during the injection of non-metallic liquids in the transparent laboratory die casting machine at various stages of die fill. Left: controlled viscosity standard S-600, viscosity = 23.0 stokes. Right: methyl alcohol, viscosity = 0.008 stokes.

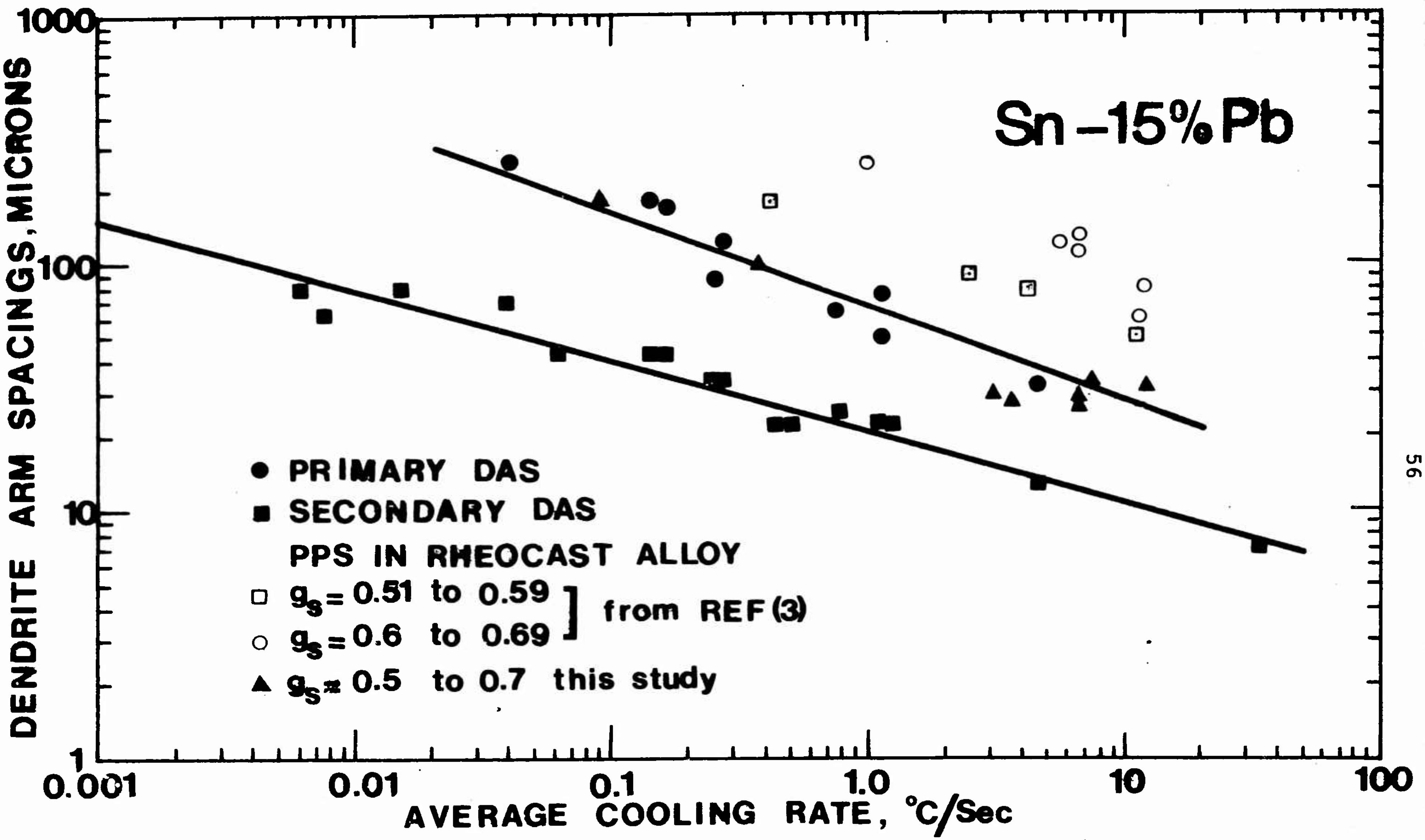


Figure 10. Variation of dendrite arm spacings, DAS, in conventionally cast, and variation of primary solid particle size, p.p.s., in continuous Rheocast Sn-15Pb alloy with average cooling rate during solidification. g_s denotes the volume fraction of primary solid particles in the Rheocast alloy.

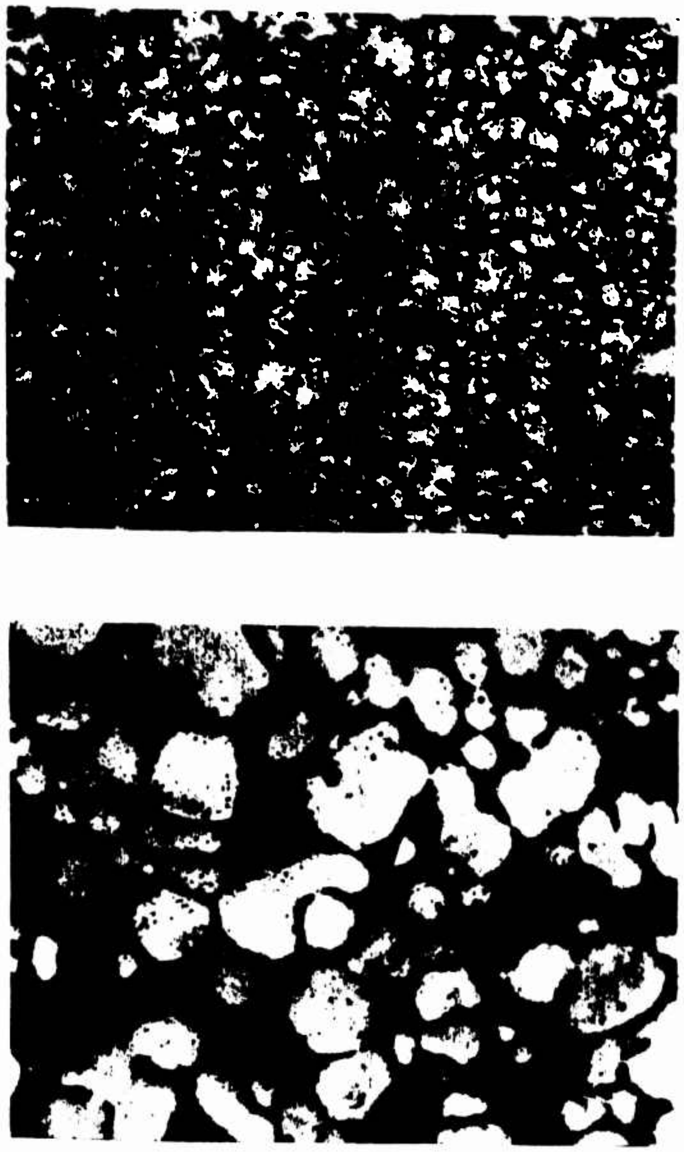


Figure 11 Microstructure of Rheocast Sn - 15wt%Pb alloy made continuously in the low temperature slurry producer. Magnifications are 100X and 250X for the top and bottom micrographs respectively.

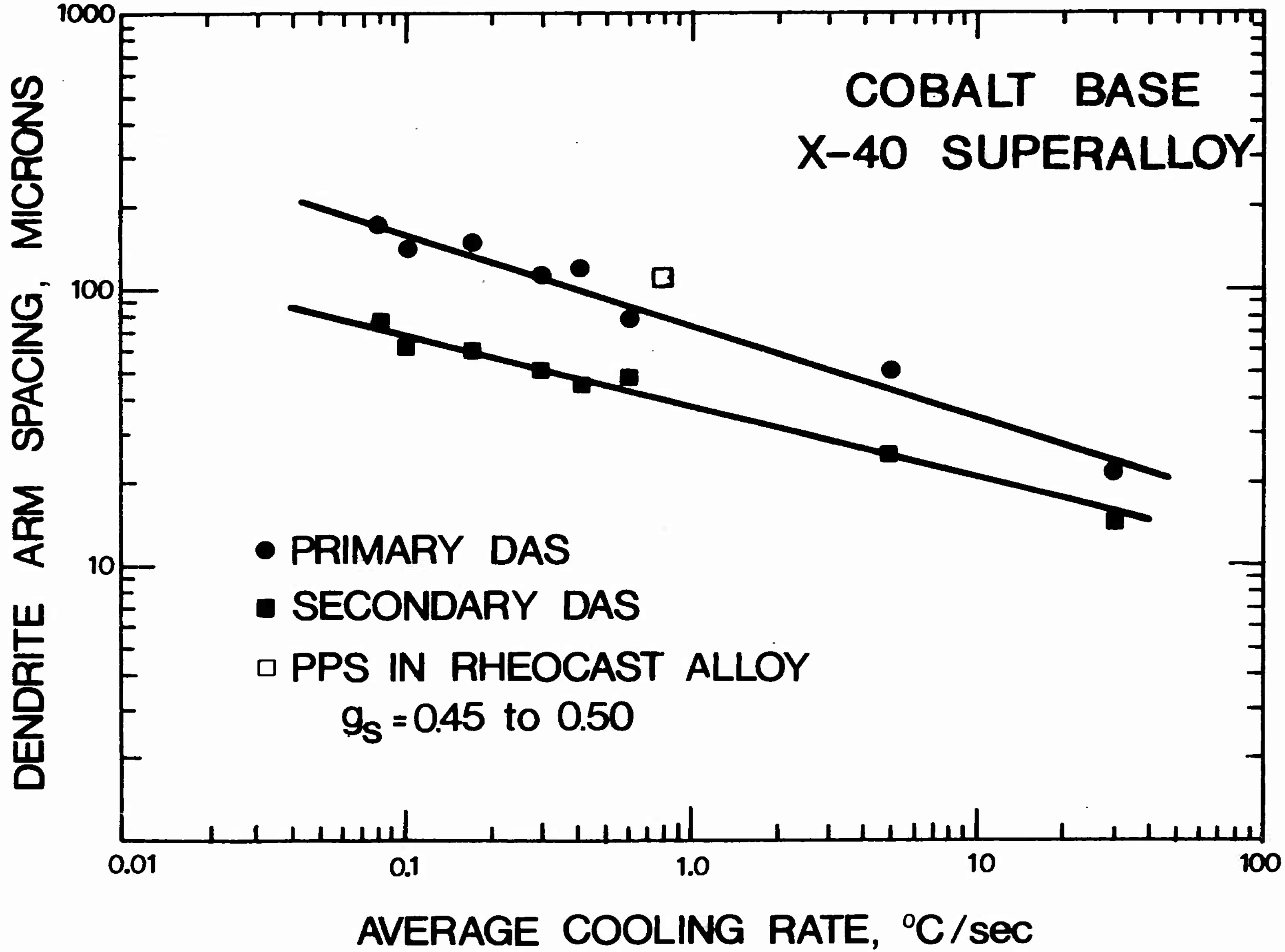


Figure 12. Variation of dendrite arm spacings, DAS, in conventionally cast, and variation of primary solid particle size, p.p.s., in continuous Rheocast X-40 cobalt base superalloy with average cooling rate during solidification. g_s denotes the volume fraction of primary solid particles in the Rheocast alloy.

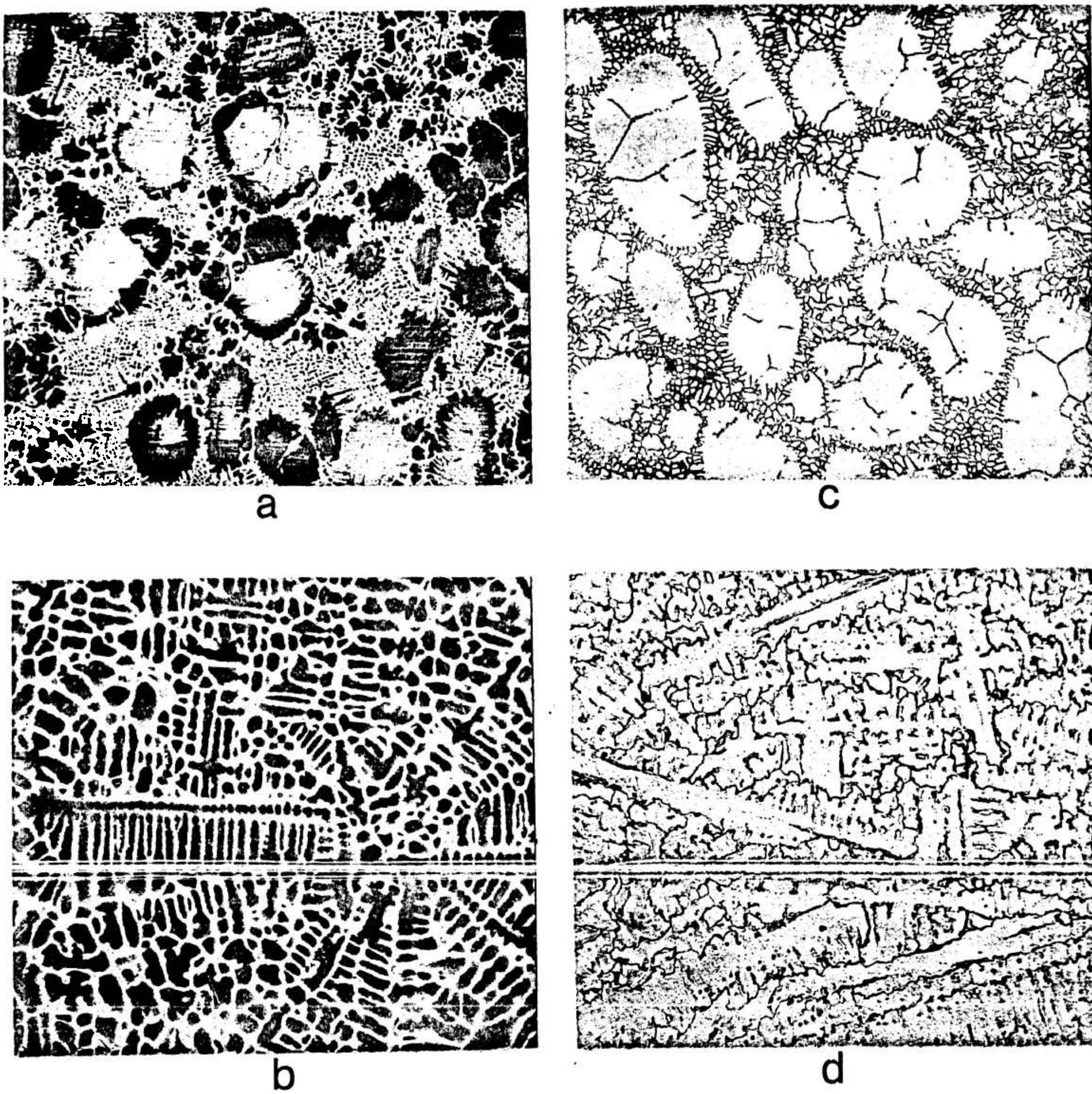


Figure 13. Comparison of Rheocast ahd conventionally cast (dendritic) microstructures of high temperature alloys solidified at equivalent cooling rates; (a) and (b) show the Rheocast and conventional dendritic microstructures of 440C stainless steel, respectively; (c) and (d) show the Rheocast and conventional dendritic microstructures of X-40 cobalt base superalloy, respectively. Magnification 100X.

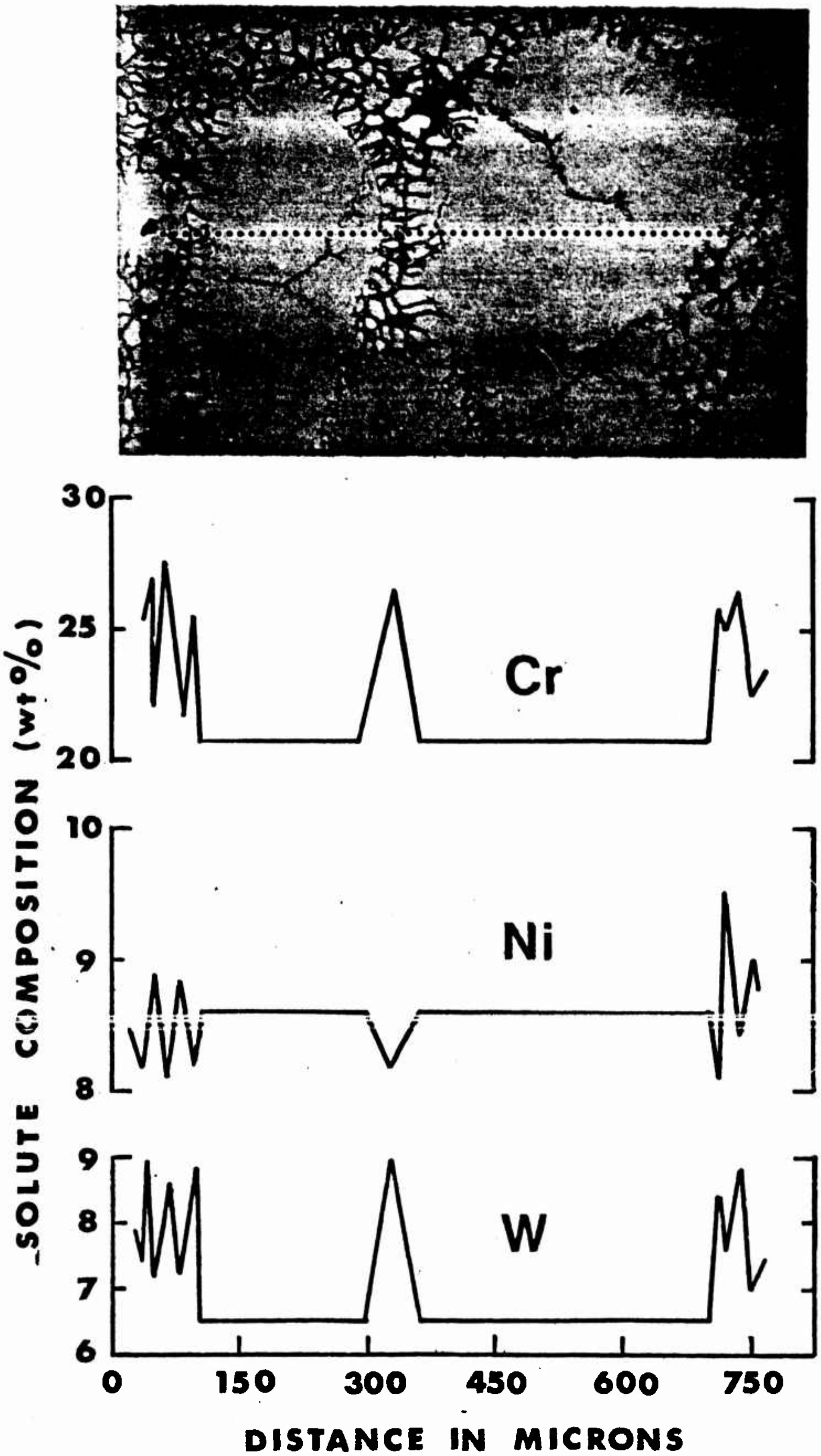


Figure 14. Composite figure showing microprobe trace and photograph of microstructure of water quenched Rheocast X-40 cobalt base superalloy. Solute distribution is along dotted path shown in the photograph. Both graph and photograph have same scale in the horizontal direction.

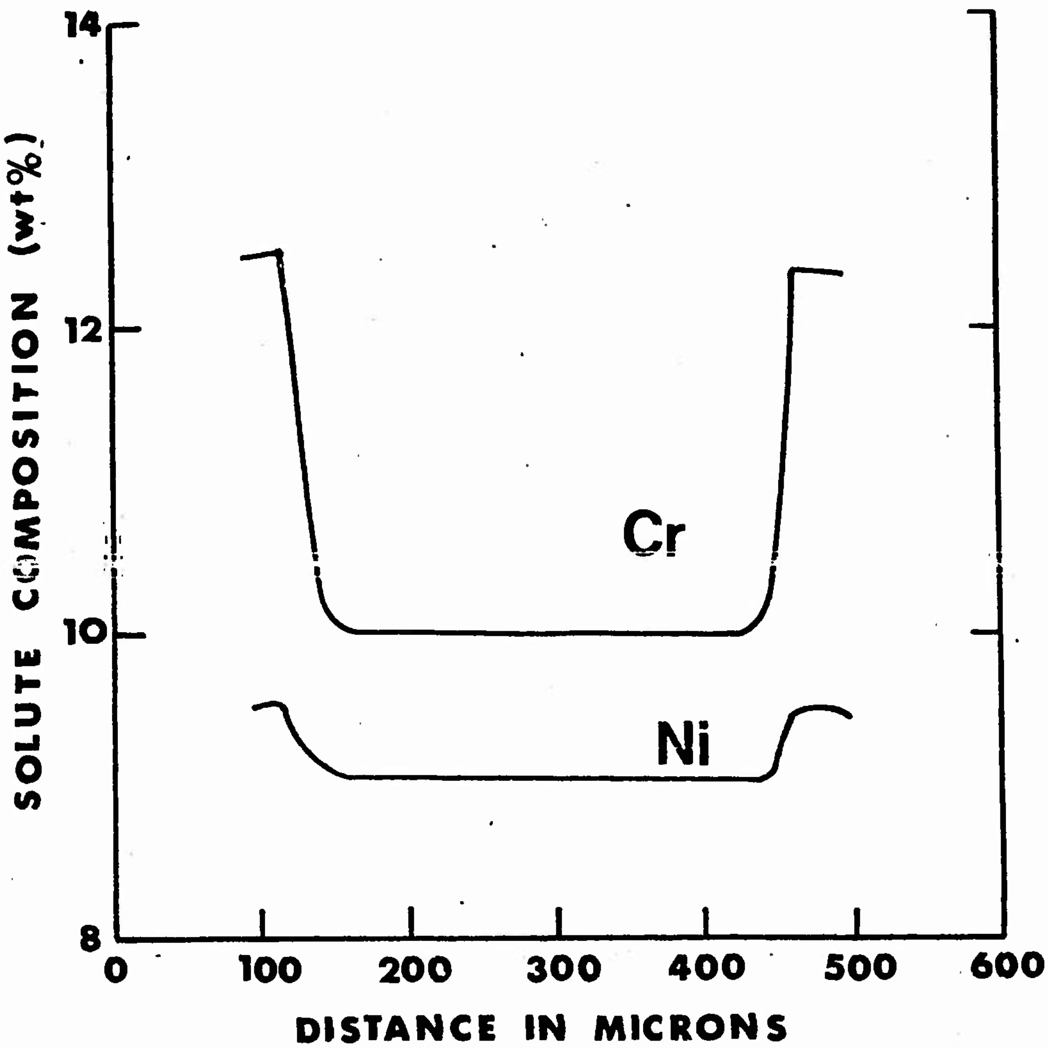


Figure 15. Composite figure showing microprobe trace and photograph of microstructure of water quenched Rheocast 304 stainless steel. Solute distribution is along dotted path shown in the photograph. Both graph and photograph have same scale in the horizontal direction.

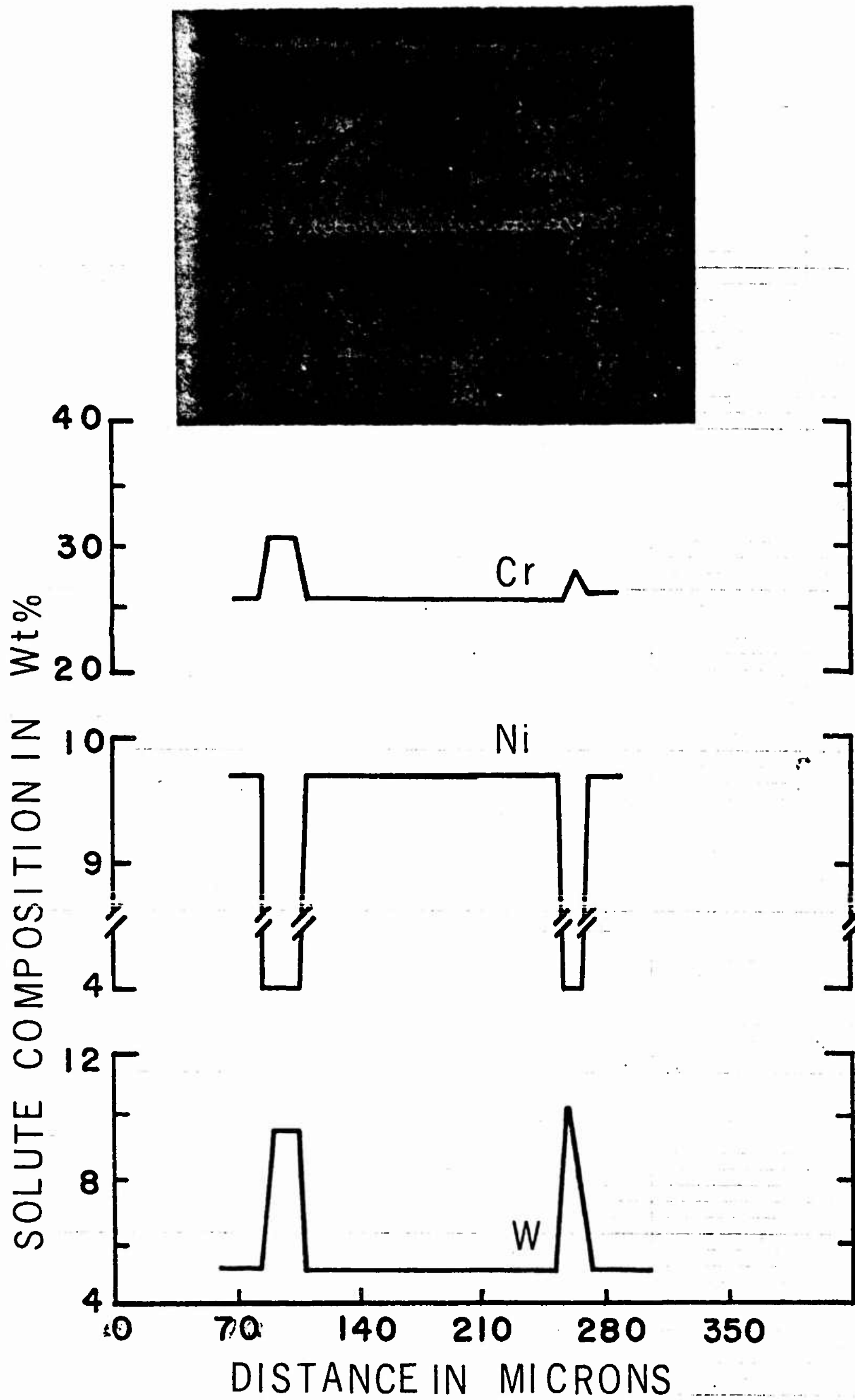
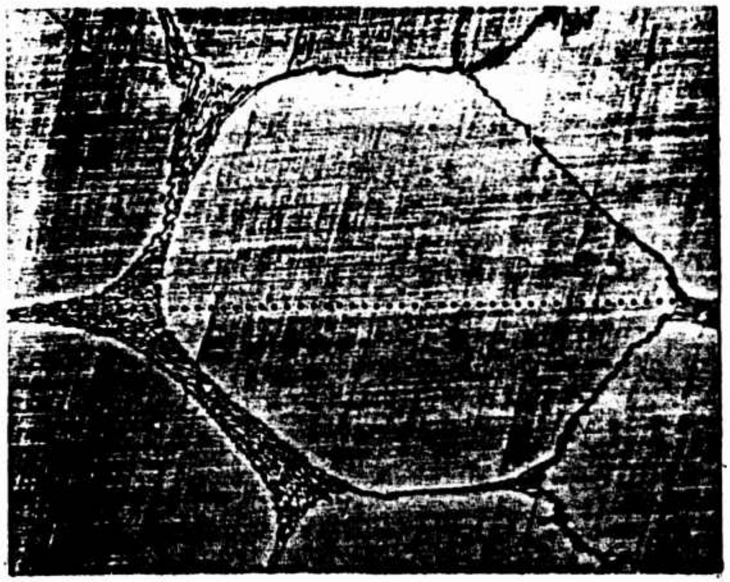


Figure 16. Composite figure showing microprobe trace and photograph of microstructure of Rheocast and homogenization heat treated (5 hours at 1300°C) X-40 cobalt base superalloy. Solute distribution is along dotted path shown in the photograph. Both graph and photograph have same scale in the horizontal direction.



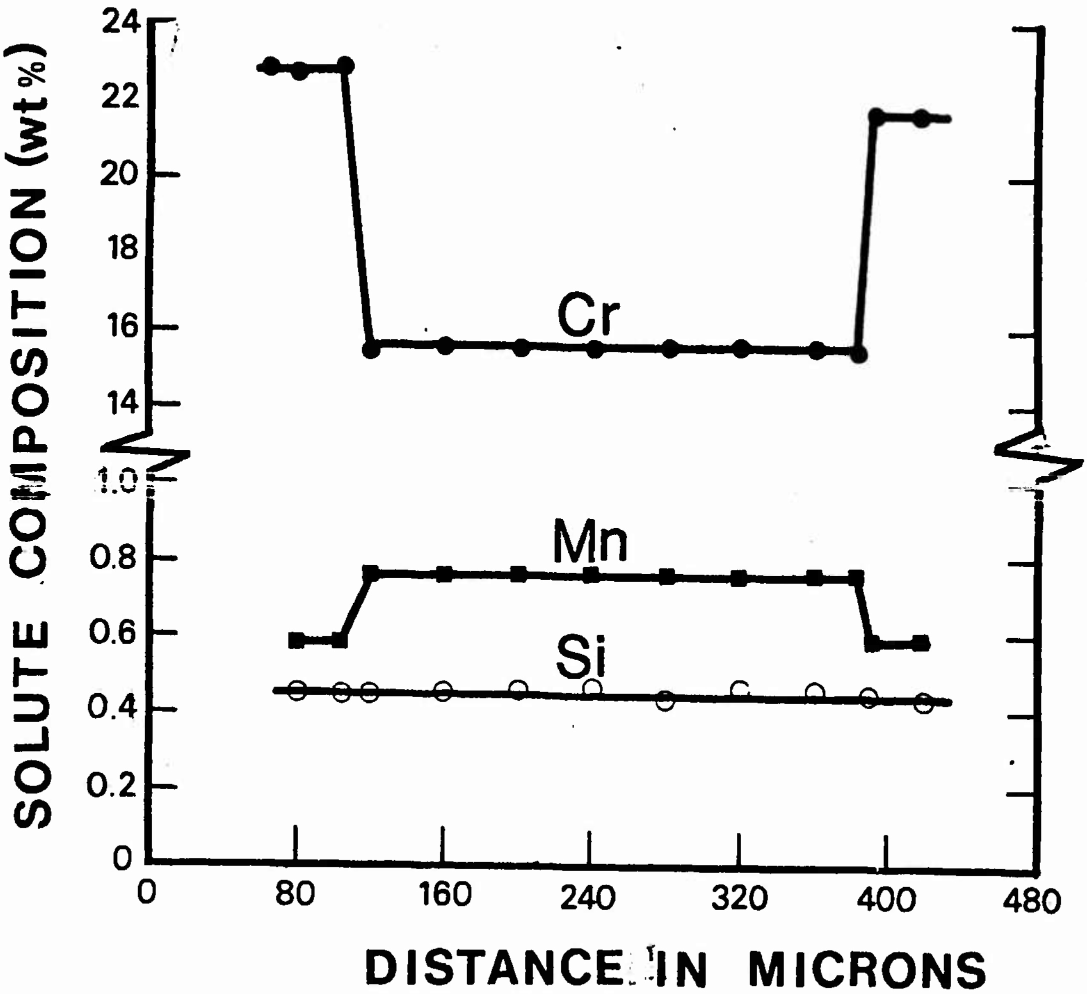


Figure 17. Composite figure showing microprobe trace and photograph of microstructure of Rheocast and homogenization heat treated (5 hours at 1300°C) 440C stainless steel. Solute distribution is along dotted path shown in the photograph. Both graph and photograph have same scale in the horizontal direction.

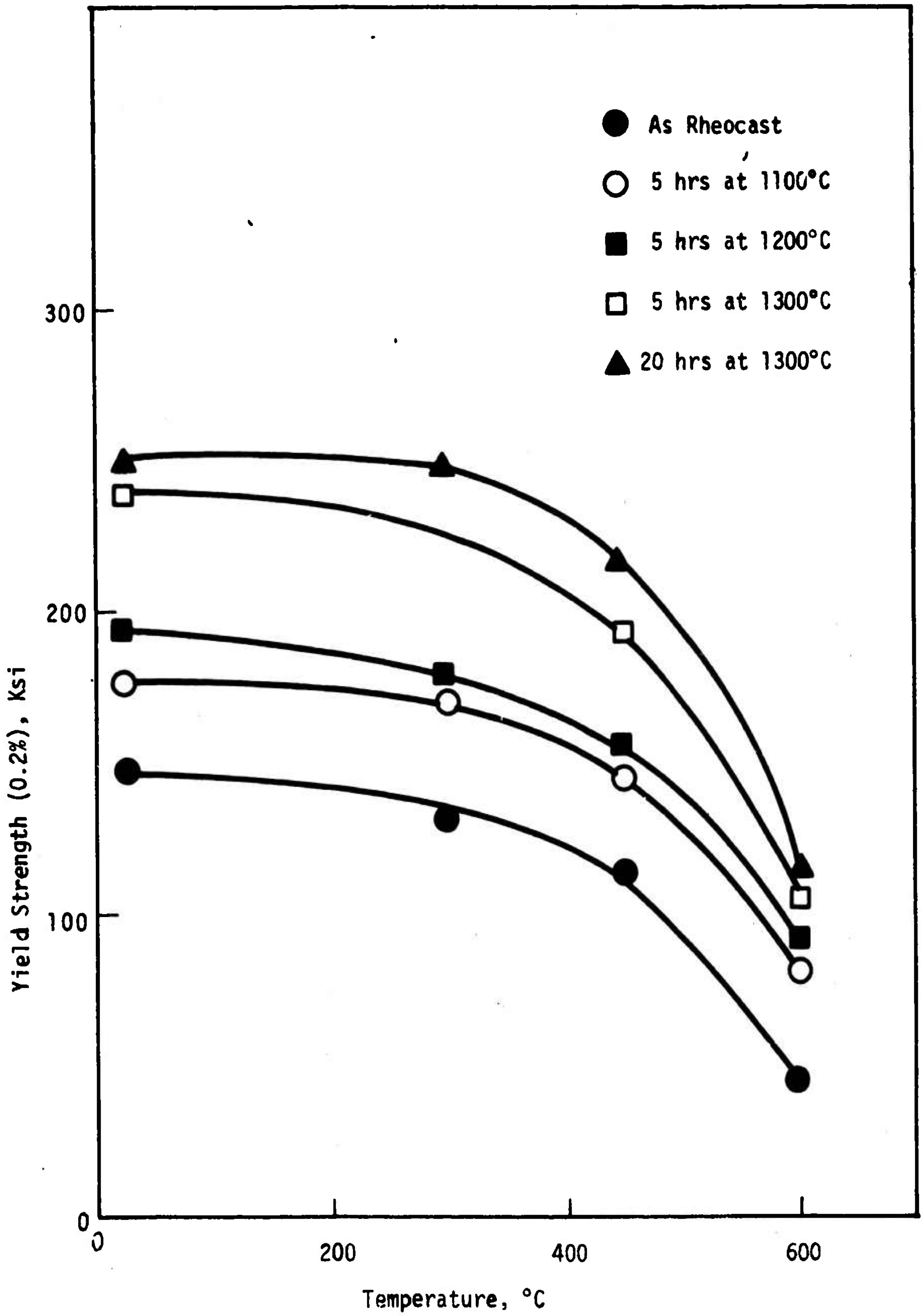


Figure 18. Measured compressive yield strength of as-Rheocast and homogenization heat treated 440C stainless steel as a function of temperature.

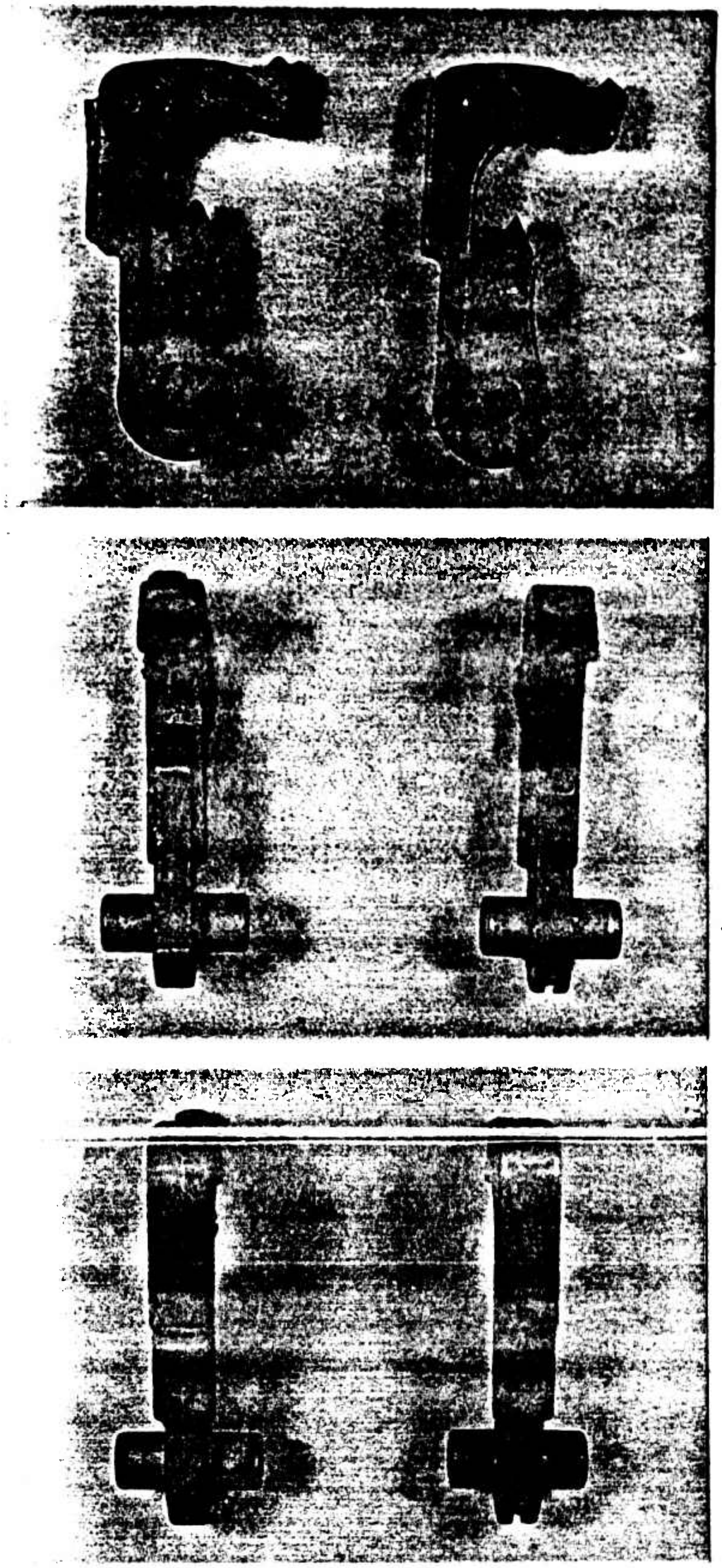


Figure 19. Photographs of M-16 Rifle Hammer. The three photographs on the left show the as-cast part. The three photographs on the right show the final machined part. Magnification 1.15X.

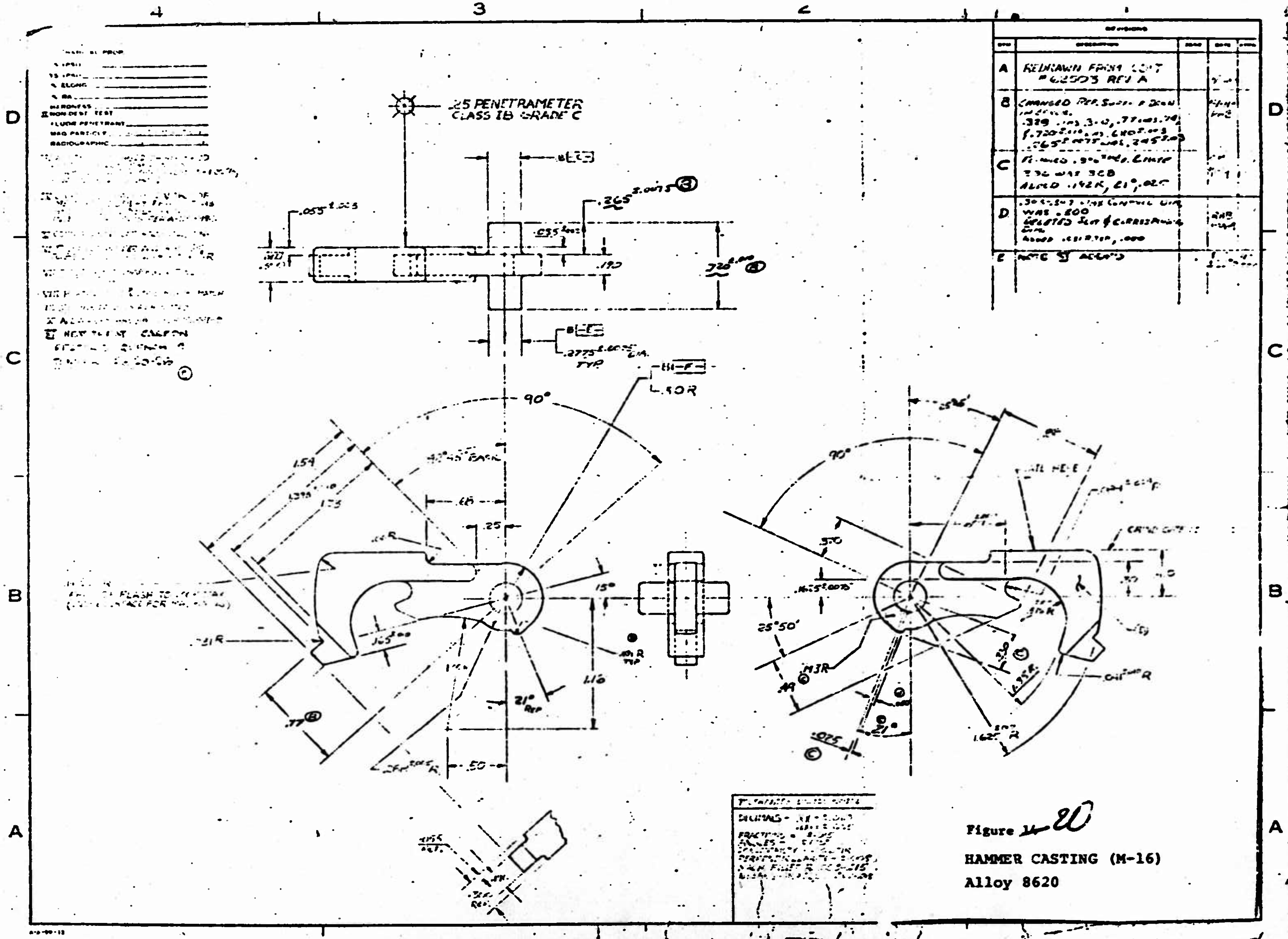


Figure 14-8C

HAMMER CASTING (M-16)

Alloy 8620

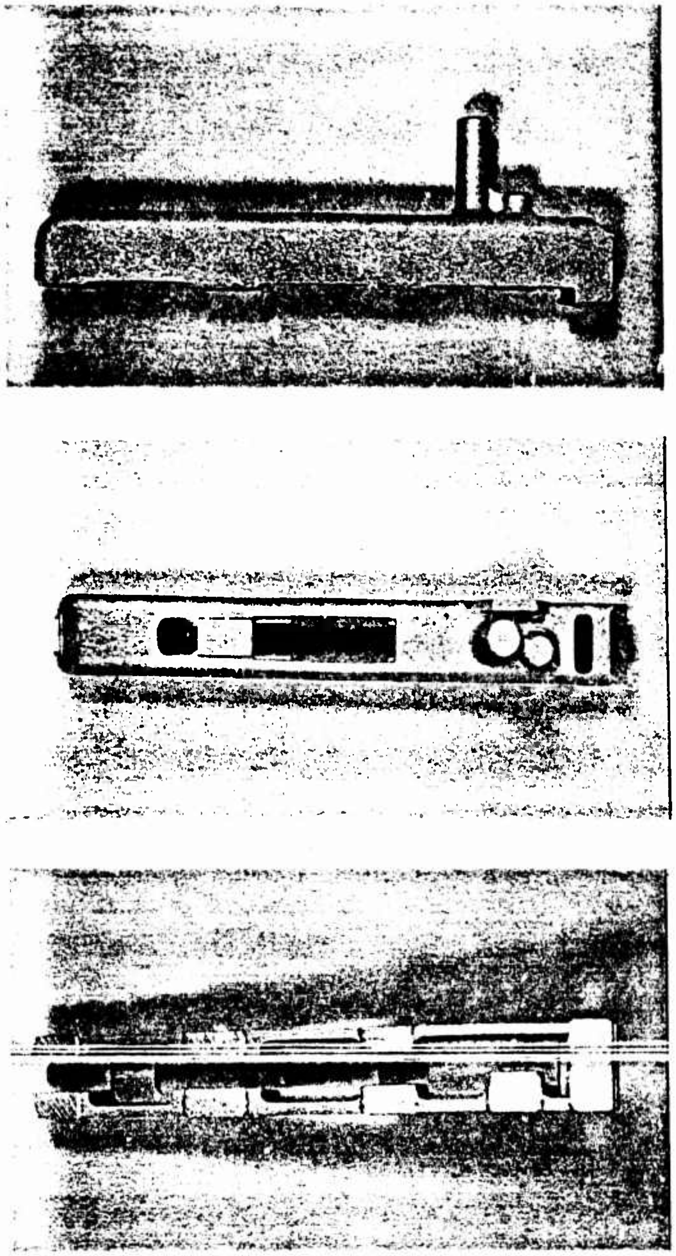


Figure 21. Photographs of the as-cast (investment) channel-trigger for the M-60 machine gun. Magnification 0.5X.